## 3.0 TECHNOLOGY ROADMAP AND PROGRAM FORMULATION

Constellation-X has achieved significant technology development progress since the beginning of its “pre-formulation” in 1996. Section 3.1 describes the current level of technology readiness, heritage, and the technology development plan for each enabling technology. Section 3.2 covers all other activities required to complete project formulation.

### 3.1 Technology Readiness and Development

The Constellation-X technology requirements and development roadmap were first documented in the Technology Roadmap in February 1997. This document defined the technologies needed for the mission, the technical path to develop these technologies, and nominal budgets. Based on these requirements, a NRA for Constellation-X technology development was issued in January 1998 and contracts awarded later that year. These contracts supported technology development of the X-ray microcalorimeter, grating, CCD, and HXT.

All required technologies are extensions of existing technologies that have been proven on previous missions. The Technology Development Roadmap in Table 3-1 summarizes the enabling and enhancing technologies, the improvements required, the current TRL and anticipated arrival of TRL 6.

Significant progress has been made on developing each of these technologies. Development efforts have leveraged off funding sources including Supporting Research and Technology (SR&T), and the Cross Enterprise Technology Development Program (CETDP), to maximize the return on limited project investments. The TRLs are currently in the 3 to 4 range, with required performance demonstrated at the component or bread board level.

The summary schedule to complete technology development is provided on Foldouts 8 and 9. Detail for each technology development showing the transition to flight instrument is provided in Appendix B. TRL 6 will be demonstrated for all technologies prior to the mission Non-Advocate Review (NAR) in late 2006. ***No flight demonstrations of the technologies are required.***

The technology development plan provides a clear path with defined milestones and attention toward minimizing risk in a cost-constrained environment. When appropriate, parallel

**Table 3-1:** Technology Development Roadmap Summary

| System | Technology | Heritage | Required Improvement | Req't | Subsystem Technology Readiness Level by Fiscal Year | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | | | | 1998 | Current | 2004 | 2005 | 2006 |
| FMA | SXT Mirror | Astro-E/E2, BBXRT, ASCA | Angular resolution | 12.5 arcsec | TRL 2 | TRL 3-4 | TRL 4 | TRL5 | TRL 6 |
| | | XMM-Newton | Larger diameter | 1.6 m | | | | | |
| RGS | Gratings (RGA) | XMM-Newton, Chandra | Low mass | 0.2 g/cm$^2$ | TRL 3 | TRL 3 | TRL 5 | | TRL 6 |
| | | | Mass production | 25/day | | | | | |
| | CCD Detector* (RFC) | Chandra, ASCA | Production yield | 20% | TRL 2 | TRL3 | TRL 4 | TRL 6 | |
| | | | Event drive | | | | | | |
| XMS | Microcalorimeter | Astro-E/E2 | Larger array | 32 x 32 | TRL 3 | TRL 4 | TRL 5 | TRL 6 | |
| | | | Energy resolution | 4 eV | | | | | |
| | ADR | Astro-E/E2 HAWC, XQC | Warmer sink | 6 K | TRL 3 | TRL 4 | | TRL 5 | TRL 6 |
| | | | Cont. operations | | | | | | |
| | Cryocooler* | HST, TES, AIRS | Lower temperature | 6 K | TRL 3 | TRL 4 | | TRL 5 | TRL 6 |
| HXT | HXT Mirrors | HEFT, InFOCμS | Angular resolution | 60 arcsec | TRL 3 | TRL 4 | TRL 5 | TRL 6 | |
| | HXT Detectors | HEFT, Swift | Low energy response | 6 keV | TRL 3 | TRL 4-6 | TRL 5 | TRL 6 | |

** Enhancing improvements; not required for mission implementation.*

approaches are pursued, which serves to mitigate risks while allowing competitive development for technologies where there is no clear determination a priori which technology is the most advantageous for the mission. Build up of sequentially more complex demonstration systems, as planned for the mirrors and XMS arrays, provides early development of components and processes.

The SXT and HXT mirrors and the RGS gratings require mass production to fabricate the large quantities required. This is factored into their development. Concepts to meet the production challenges for the flight build have been established and are summarized in the discussions of each technology.

***Technology Development Risk and Mitigation:*** The technology development phase risks are summarized in Table 3-2, with assessments of their criticality and likelihood of occurrence, if no mitigation activities are implemented. These risks will be retired by the time mission implementation begins. The implementation phase risks are summarized in Table 4-3.

The mitigation plan for each risk is also provided. The criteria for evaluation of criticality and likelihood are:

- Criticality:
  - —**High:** increases mission budget >3%; or delays launch date; or degrades performance below minimum science requirements
  - —**Medium:** increases mission budget 1-3%; or delays major mission milestone >2 months; or degrades performance below baseline science requirements
  - —**Low:** increases mission budget <1%; or delays major mission milestone ≤2 months; or loss of design margins
- Likelihood:
  - —**High:** >50% probability of occurrence
  - —**Medium:** 25-50% probability
  - —**Low:** <25% probability

### 3.1.1 SXT Mirror Technology Readiness and Development Plans

#### 3.1.1.1 SXT Mirror Technology Readiness

The SXT mirror requirements have been provided in Section 1.3.1.1. The mirror will have a diameter of 1.6 m and a focal length of 10 m.

***Technology Description:*** The SXT mirror design is a segmented, highly nested Wolter I. The mirror consists of 18 modules, 6 inner and 12 outer. Reflectors are 440 $\mu$m thick glass, 20-30 cm long, and subtending a 60 degree arc in the inner module, 30 degrees in the outer. They are thermally formed to a precise figure, with a gold X-ray reflecting surface imparted via epoxy replication.

CX015

**Figure 3-1:** Astro-E flight mirror has a 40-cm diameter and a mass of 17 kg. The design utilizes tightly nested, segmented epoxy-replicated reflectors. The SXT mirror is based on this approach, scaled to 1.6 m, incorporating more accurate replication mandrels, more stable reflector substrate, and more precise alignment.

The heritage of the SXT mirror is addressed in Section 1.3.1.1. The closest predecessors are those flown on BBXRT, ASCA, XMM-Newton, and Astro-E/E2 (Figure 3-1). This style of mirror meets the Constellation-X mass requirement. The mass production approach for these mirrors serve as a model for the SXT mirror. Previous foil mirrors had conical optical surfaces; the SXT mirror will have a Wolter-I (axially curved) surface. The fabrication steps for the SXT mirror are similar to those for the conical thin-foil mirrors. In particular, the SXT mirror uses the identical method of epoxy replication for creating X-ray reflecting surfaces, in which a thin layer of epoxy is sprayed onto the reflector substrate and used to impart a final optical surface replicated from an ultra-smooth, precise mandrel. The higher angular resolution requirement of the SXT mirror has necessitated substantial development of new processes. These include the use of new substrate material (glass), forming process (slumping) and

**Table 3-2:** Technology Development Risk Summary

| Technology | Reference | Risk | Mission Impact | Criticality | Likelihood if no Mitigation | Mitigation |
|---|---|---|---|---|---|---|
| SXT Mirror | SXT-1 | Reflectors do not meet angular resolution at the required dimensions | Reduces mass reserves, no science impact | Medium | Low | Use thicker substrates |
| | | | Reduces throughput margin, remains above Mission Minimum Effective Area Requirement | Medium | Low | Use smaller reflectors |
| | SXT-2 | Unable to verify mirror performance in 1 g | Does not meet image performance requirement | Medium | Low | Design for 1 g analysis<br>Fabricate vertical test facility |
| RGS Gratings | RGA-1 | Thin substrates do not achieve required flatness | Reduces mass reserves and/or reduce grating area and/or schedule impact | Medium | Low | Use same production scheme as XMM Newton RGA |
| | RGA-2 | Inability to efficiently mass produce gratings | Reduction of grating area<br>Reduces schedule reserves | Medium/ Low | Low | Use same production scheme as XMM Newton RGA, use thicker substrates. Parallel study off-plate gratings |
| RGS CCD Detector | CCD-1 | MBE yield lower than anticipated | Reduces funding reserves; schedule impact | Low | Medium | Use existing BI X-ray CCDs (TRL 9) |
| | CCD-2 | EDCCD circuitry impractical | Larger power consumption, decreased timing resolution | Low | Low | Disable EDCCD feature |
| XMS Microcalorimeter | XMS-1 | TES detector does not meet 4 eV requirements | Does not meet spectral resolution performance requirement | Medium | Low | Parallel TES and NTD/Ge development; reoptimize array geometry |
| | XMS-2 | High density array interconnects | Use schedule reserves | Medium | Low | Parallel approaches in development; stacked insulated leads; reoptimize array |
| | XMS-3 | SQUID MUX Speed | Lower margin on ADR cooling | Low | Medium | Trade number of MUXed channels with heat load and complexity |
| XMS ADR | XMS-4 | ADR heat rejection Incompatible with cryocooler | Detector “livetime” is limited | Medium/ Low | Low | Design cryocooler and ADR with significant margin; cycle ADR more frequently |
| | XMS-5 | SQUID noise from magnetic fields | Lowered energy resolution | Low | Low | Fund superconducting wire fab.<br>Install magnetic shielding |
| XMS Cryocooler | XMS-6 | Required cooling efficiency not achieved | Reduces mass, funding, and schedule reserves; limit mission life | Medium | Medium | Use alternate cryocooler under ACTDP<br>Parallel development<br>Use hybrid 35 K cryocooler with stored cryogen |
| HXT Detectors | HXT-1 | Do not reach low-energy threshold | Reduced overlap with XMS for calibration | Low | Medium | Electronics architecture redesign |

mounting approach (precision mounting of individual or small groups of reflectors, in contrast to gang alignment of an entire module).

The SXT program will benefit from prior reflector mass production efforts, including those for the conical mirrors and for XMM-Newton. The SXT program also makes extensive use of systems and thermal engineering experience from Chandra, utilizing a similar alignment approach (though on a larger scale), using the CDA that was developed for Chandra. Equally important, the SXT mirror technology development approach has similar key milestones to the highly successful Chandra mirror development: production of a small prototype, followed by a demonstration that the largest mirror can be fabricated, prior to the production of the flight mirror system.

***TRL Status:*** At the start of technology development, the thin foil mirror from which the SXT mirror draws its heritage had already flown on several space missions (TRL 9). The current design, with its large radius, new materials and new production process, was at a much less mature level (TRL 2).

Currently, the SXT mirror system as a whole is at TRL 3-4, with all components at TRL 4 or higher. A pathfinder module has been designed, analyzed, and assembled. The performance of this module has been shown to meet expectations based on analysis, providing confidence in the analytical models.

A pathfinder housing has been built that has been shown to be able to adjust a reflector over the range and with the accuracy necessary to align flight mirrors. Reflectors have been fabricated using the flight development approach that satisfies the error budget (Table 1-3); the process is currently being scaled to full-sized reflectors. Metrology and alignment procedures for individual reflectors have been developed and demonstrated. The largest replication mandrel needed for the flight mirror has been delivered; it meets or exceeds specifications.

#### 3.1.1.2 SXT Mirror Technology Development Plan

***Strategy and Logic:*** The major steps in the SXT mirror technology development plan are described below. Some key principles underlying this plan are:

- maximum use of existing facilities for metrology and calibration
- reuse of previous technology developments
- development and demonstration of all processes for assembly, alignment, and bonding, and transfer of these to industry
- progressive build toward flight prototype (see details below); attacking the "tall poles" in the error budget first, and solving problems incrementally as they are encountered
- design and test supported by full analysis (finite element mechanical and thermal analysis plus optical ray tracing)

***Technology Development Plan:*** The SXT mirror technology development relies on progressive development from components to a full prototype. Starting with relatively simple units, progressively higher complexity is added in each step along the development path, allowing a careful study of all key fabrication, assembly, and alignment issues. The end product is a full-size segment of a SXT mirror that will be fully environmentally and performance qualified. A representative group of reflector pairs will be incorporated, spanning the full range of diameters, and ensuring that the prototype has sufficient fidelity to the flight unit. The technology development plan is summarized in Table 3-3.

The key steps in the technology development plan are summarized below. Some of these steps are called out specifically in Table 3-3, while some are precursor or parallel activities. Four key stages in the progressive development are identified in Table 3-3. These are the Optical Alignment Pathfinder (OAP), the Engineering Unit (EU), the Mass Alignment Pathfinder, and the Flight Prototype.

- Refining processes for reflector forming, replication, and cutting.
  - —Individual freestanding reflectors must have an RMS figure error <7 arcsec. This constrains the figure error introduced during thermal forming and the surface quality obtained from epoxy replication. Small (20-30 cm diameter by 10 cm length) reflectors meeting this requirement are being produced on a regular basis. Scaling to flight-sized reflectors (50 cm diameter by 20-30 cm length) is underway.
  - —The modeling of the effect of the thin epoxy layer on reflector mechanical and thermal properties must be verified. The epoxy shrinks while curing, introducing

**Table 3-3:** SXT FMA Technology Development Roadmap

| | Optical Assembly Pathfinder | | Engineering Unit | Mass Alignment Pathfinder | Prototype | |
|---|---|---|---|---|---|---|
| | OAP #1 | OAP #2 | | | | |
| Configuration |  |  |  |  |  |  |
| Module type | Inner | Inner | Inner | Inner | Outer | Wedge (2 Outer & 1 Inner) |
| Housing material | Aluminum | Titanium | Composite | Composite | Composite | Composite |
| Focal length | 8.5 m | 8.5 m | 8.5 m | 8.5 m | 10.0 m | 10.0 m |
| Reflector length (P&H) | 2 x 20 cm | 2 x 20 cm | 2 x 20 cm | 2 x 20 cm | 2 x 20-30 cm | 2 x 20-30 cm |
| Nominal reflector diameter(s) | 50 cm | 50 cm± | 50 cm± | 50 cm± | 160 cm<br>120 cm±<br>100 cm | 160 cm±;40 cm±<br>120 cm±<br>100 cm± |
| Goals | • Align 1 reflector pair (P&H)<br>• Evaluate mirror assembly design, alignment and metrology | • Align 1 reflector pair<br>• Evaluate reflector gravity sag<br>• Evaluate mirror bonding | • Align up to 3 reflector pairs to achieve <12.5 arcsec<br>• Eval. assembly gravity sag<br>• X-ray and environmental test<br>• Evaluate composite housing | • Align 3 reflector pairs<br>• Evaluate tooling and alignment techniques for mass production<br>• X-ray test | • Flight-like configuration outer module<br>• Environmental and X-ray test<br>• Largest reflectors | • Demonstrate largest and smallest diameter reflectors<br>• Demonstrate module to module alignment<br>• Environmental and X-ray test |
| Timeframe | Q2 of FY03 | Q3 of FY03 | Q1 of FY04 | Q1 of FY05 | Q4 of FY05 | Q4 of FY06 |

stress in the reflectors. Mismatch of its thermal properties with the glass places constraints on temperature gradients. The degree of distortion will be quantified and verified that its properly accounted for in the error budget.

—Cutting the reflector edges to an accuracy of 20 $\mu$m is required for some of the mass alignment approaches being explored.

- Synergistic with the reflector fabrication is the requirement on the mandrels used for forming and replication. Forming mandrels must remain stable when cycled to 600° C. Replication mandrels require a figure precise enough to allow a minimum epoxy thickness to be used. Significant research is being performed to determine cost-effective materials and fabrication approaches.
- The distortions introduced when a reflector is placed in a housing and aligned must be understood and shown to remain within the error budget[36]. [OAP1]
- Means for bonding an aligned reflector into a housing without introducing unacceptable distortions will be developed. [OAP2]
- A matched paraboloid (P) and hyperboloid (H) pair must be aligned, forming an image that meets the 12.5 arcsec HPD angular resolution requirement. [OAP2]
- Reliance must be placed on analytical modeling of the effects of temperature and gravity on alignments. Smaller, simpler units are to be used early in the program to validate and verify the model predictions. [OAP2]
- The near term critical milestone for the SXT technology development is a demonstration in X-rays of the required imaging performance of a reflector pair after environmental tests. This demonstration will take place in early FY04. [EU]
- Incorporating flight compatible housing materials such as carbon fiber composite with engineered CTE will reduce sensitivity to temperature effects. [EU]
- Alignment of a reflector pair without introducing misalignment into previously aligned

and bonded pairs, will be demonstrated. X-ray imaging performance will be verified before and after environmental testing. [EU]

- An approach will be developed for the rapid assembly and alignment of a module, with simultaneous alignment of multiple reflector pairs to meet the angular resolution requirement. [Mass Alignment Pathfinder]
  - —A current approach uses microcombs (accurate to <0.1 $\mu$m) that have already been fabricated (see Foldout 3-B8 and 3-D18).
  - —Rapid, computer-controlled alignment of individual pairs will also be investigated.
- Fabricating the largest (1.6 m) reflectors requires development of infrastructure at the scale needed for flight mirror production. Infrastructure items are forming and replication mandrels, associated handling equipment, a robotically controlled epoxy spray station, coating and replication chambers, a precision glass-cutting fixture, and metrology equipment. The possibility of producing longer reflectors will be investigated: longer reflectors require fewer nestings, fewer forming and replication mandrels, and is a potential cost savings. [Outer Prototype]
- A flight-like unit will be assembled and shown to meet requirements through X-ray and environmental testing. [Outer Prototype]
- Three flight-like units will be co-aligned and X-ray tested. [Wedge Prototype]
- A flight prototype will be integrated with a prototype grating, and the performance of the combined unit measured in X-rays. [Wedge Prototype]

***Technology Investments to Date:*** Investment in the segmented approach has resulted in the establishment of an infrastructure for producing the OAP units. This includes precision replication mandrels, forming mandrels, a forming oven, an epoxy spray station, glass cutting fixtures, a replication chamber, metrology equipment, alignment housings, and Si microcombs (Foldout 3-A and 3-B).

Initially, the segmented mirror technology was developed in parallel with full shell mirrors fabricated via nickel electroforming. The full shell approach was abandoned when it became apparent that the required massive, monolithic mandrels would be impossible to fabricate. The segmented program has utilized much of the infrastructure originally produced for the full shell approach, including the EU replication mandrels and several pieces of metrology equipment.

***Test Beds and Simulators:*** The facilities at GSFC used for prototype development serve as test beds for SXT mirror fabrication. A reflector development laboratory is being used to establish the facilities and processes that will be incorporated into a reflector production facility, and an optical alignment test bed has been developed to define processes for assembling and aligning reflectors within housings.

***Equipment and Facilities for Technology Development:*** The SXT mirror program has maximized use of existing equipment at GSFC, MSFC, and SAO. Equipment has been modified or upgraded to meet SXT needs when this was deemed more cost effective than new equipment. Examples of reuse of existing equipment and facilities are: (1) use of optics fabrication facilities at GSFC and MSFC for pathfinder mandrel development; (2) use of existing metrology equipment (WYKO microscopes, coordinate measurement machines, and interferometers); (3) use of the CDA; and (4) planned use of long beam X-ray facilities at MSFC.

At this time, nearly all facilities and equipment needed for the completion of the SXT mirror technology demonstration are either on hand or on order. Equipment bought specifically to support the SXT mirror includes: (1) the contents of the GSFC reflector development laboratory–forming oven, spray booth, precision cutting fixture, storage and transport apparatus, and clean room enclosures; (2) the SXT mirror alignment facility large interferometer (on order); folding mirrors, large retroreflector, and CDA (on loan); (3) MSFC metrology equipment–horizontal and vertical long trace profilometers.

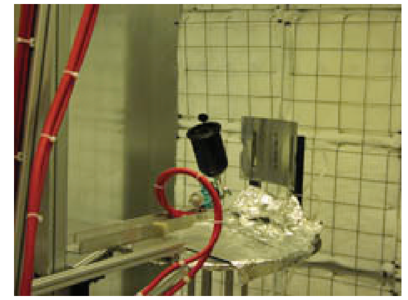
***Plans for Mandrel and Mirror Production:*** The acquisition strategy for the SXT mirror flight production entails partnering with a mirror contractor as early as possible. The Constellation-X project will solicit contractors for a six-month prototype design study starting late in FY03. On the basis of the study outcome, one contractor will be selected at the end of FY04 as the SXT contractor. The contractor will set up a reflector production facility, incorporating processes transferred from the SXT

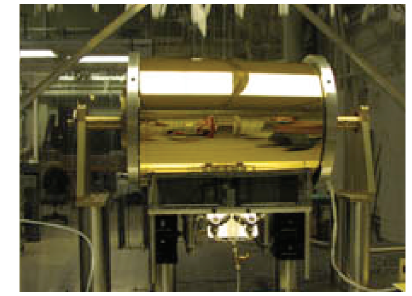
# Constellation-X Optics

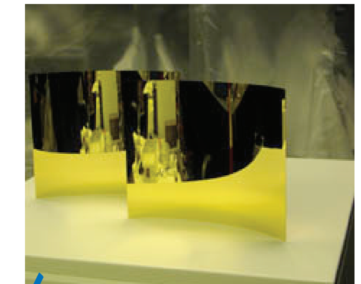
## A Spectroscopy X-ray Telescope (SXT) Mirror Reflector Replication


1) Prototype segmented replication mandrel for 1.6 m diameter reflectors. This Zeiss Mandrel, composed of Zerodur, is the largest mandrel needed for the SXT mirror.

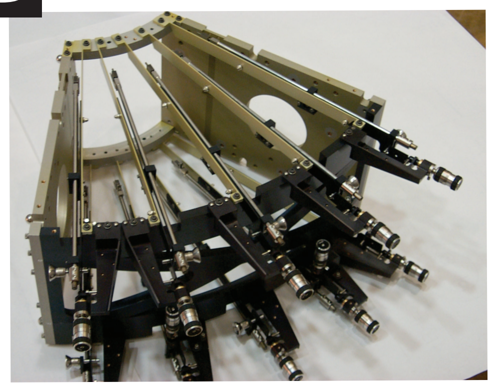

2) Thermal forming of glass reflector substrates in 1.5m$^3$ GSFC furnace. Mandrels have 20 cm diameter. The substrate material is Desag D263 glass.

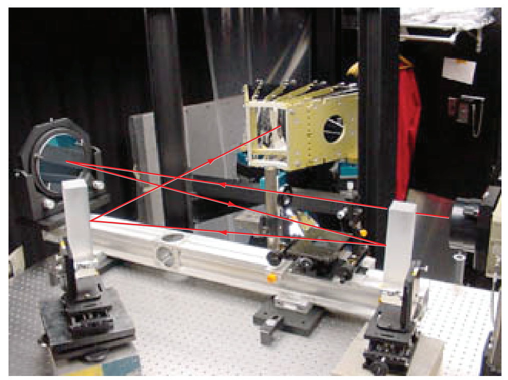

3) Epoxy application on glass substrate using robotic sprayer. Typical epoxy thickness is 10-20 $\mu$m; epoxy thickness is accurate to 1 $\mu$m.

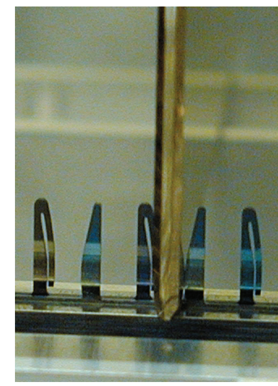

4) Attachment of glass substrate to 50 cm replication mandrel. Attachment is performed under vacuum, in housing from below. Replicas from this mandrel will be used for the Optical Alignment Pathfinder (OAP) and Engineering Unit (EU).

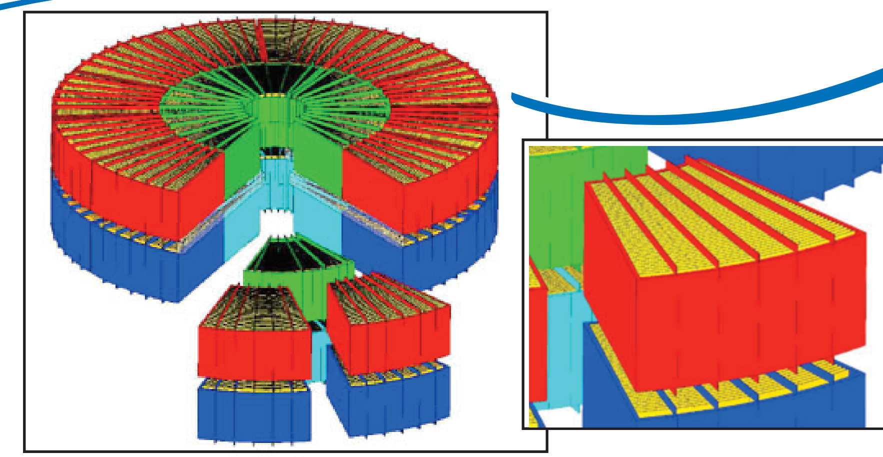

5) Final replicated glass segment. The segment subtends a 60-degree arc with a 25 cm radius of curvature. Its height is 20 cm.

## B SXT Mirror Assembly and Alignment

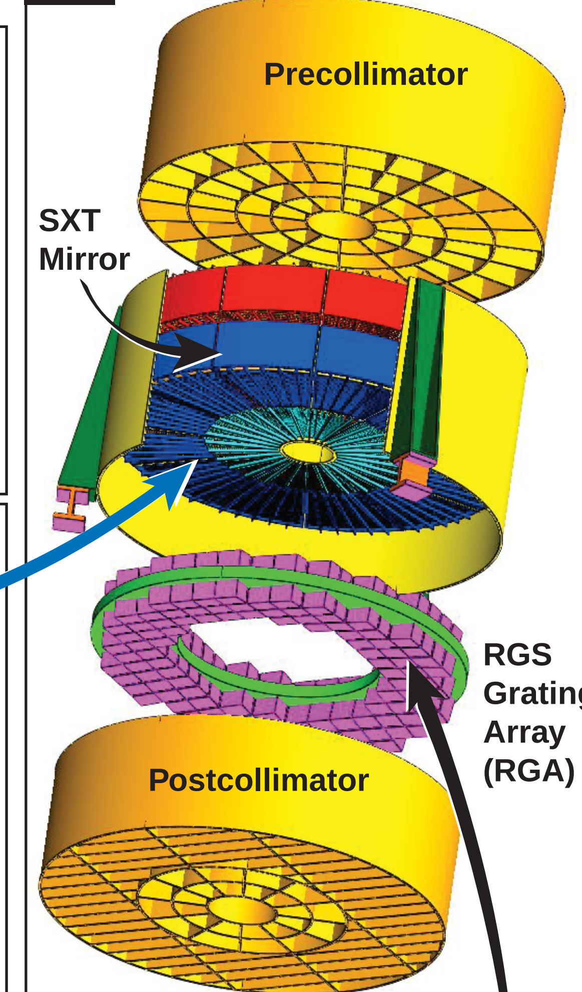

6) Reflector alignment housing for OAP-1. Housing is constructed of aluminum and has precision actuators at five azimuthal locations top and bottom to position a reflector to submicron accuracy. OAP-1 has two identical, stacked housings, for primary and secondary reflectors.


7) OAP alignment using the Centroid Detector Assembly (CDA). Red line indicates light beam path between CDA (not shown) and reflector.


8) Etched Si microcombs for mass alignment of reflectors and gratings. Microcombs are accurate to 0.1$\mu$m.

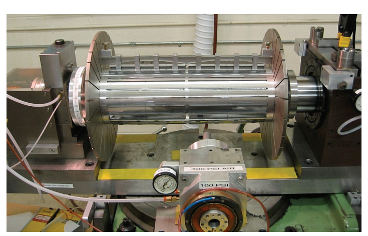

9) Concept drawing of the SXT Mirror. The mirror consists of 6 inner 60-degree modules and 12 outer 30-degree modules. Each module consists of a primary and secondary housing, each 20 cm tall. The total number of nested reflector pairs is 230; the overall diameter of the mirror is 1.6 m. Inset: Close up view of an outer module, showing radial reflector mounting struts.

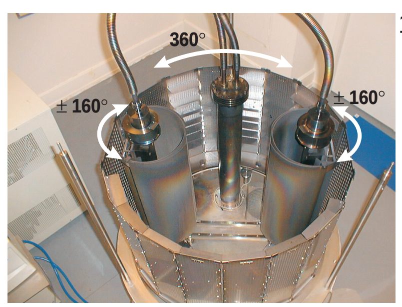
## E SXT Flight Mirror Assembly



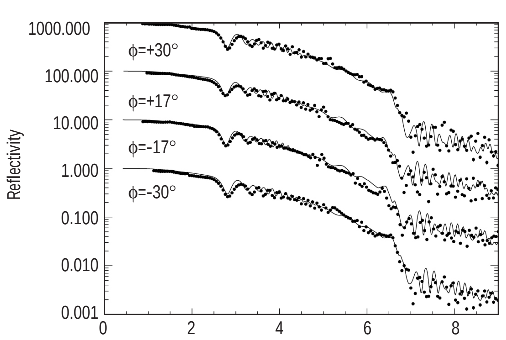
10) Exploded view of the SXT Flight Mirror Assembly (FMA) design concept.

## C HXT Mirror

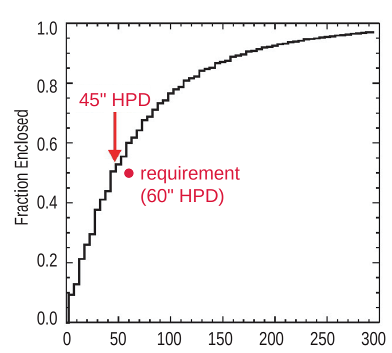

11) Glass prototype segments being assembled on a custom machine.



12) Top view of the custom magnetron sputtering facility at the Danish Space Research Institute.

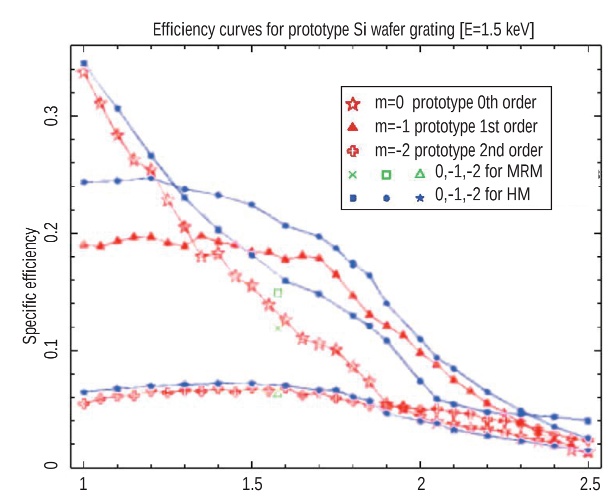


13) Measured reflectivity at 34 keV of a formed glass substrate coated with a W/Si graded multilayer, plotted in terms of incidence angle. Phi is the azimuth angle around the shell. Points are data; solid lines are model.

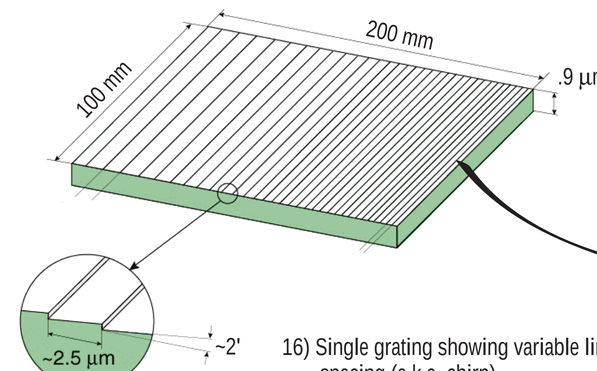


14) Measurement of performance of a prototype HXT mirror. This prototype exceeds the HXT angular resolution requirement.

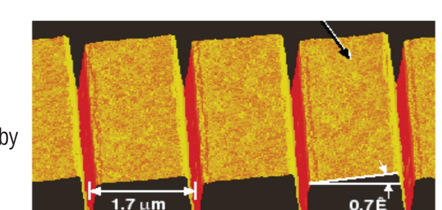
## D RGS Gratings



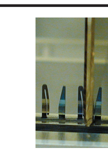
15) X-ray efficiency measurements for a prototype Si wafer grating at 1.5 keV (8.34Å), compared to master gratings. Red: test ruling: blue holographic master (HM); green: mechanically ruled master (MRM).

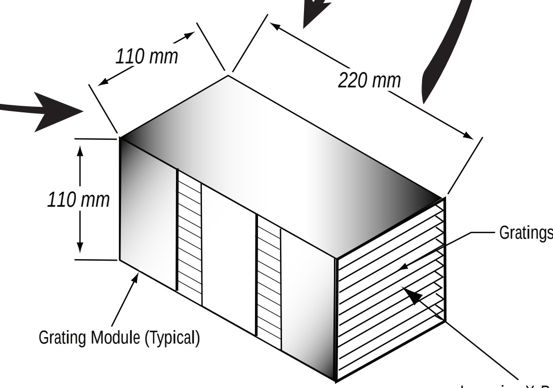


16) Single grating showing variable line spacing (a.k.a. chirp).



17) Micrograph of an anisotropically etched test ruling grating with atomically smooth groove facets, formed by Si (111) planes in the crystal.


18) Si microcombs are used for both the SXT Mirror and the RGA.



19) Grating flight module concept showing 10 identical gratings within the module.

technology development. Forming and replication mandrels will be acquired by the SXT team under separate contract, and supplied as GFE to the contractor. The contractor will be responsible for construction of reflector housings, integration and alignment of modules, full mirrors, and the FMA. The RGA will be delivered as GFE for integration into the FMA.

The SXT team has investigated the feasibility of this approach through discussions with potential partners including Kodak, Goodrich, and Lockheed Martin. Vendors for forming and replication mandrels have been identified through the procurement of prototypes. Carl Zeiss (Oberkochen, Germany) is under contract to fabricate three replication mandrels for the flight prototype (30-degree segments with radii of 1.0, 1.2 and 1.6 m). Zeiss has delivered the 1.6 m mandrel (the largest one necessary for the flight program) on schedule and meeting or exceeding specifications. Other vendors that should be capable of producing replication mandrels have expressed an interest. Several vendors have been identified that could provide some or all of the forming mandrels, including Schott Glas (Mainz, Germany) and Rodriguez Precision Optics (Lafayette, LA).

#### 3.1.1.3 Key Risks and Mitigation

The key technical risks during the SXT technology development phase are shown in Table 3-2.

***Reflector Substrate (SXT-1):*** The ability to make reflectors with the required figure and dimensions will be demonstrated. There is a low-probability, medium-criticality risk of not meeting the requirements. Mitigation will be achieved through either increasing substrate thickness (at the cost of mass), or making smaller reflectors (trading either a more complex design, or a loss of throughput).

***Performance Verification (SXT-2):*** The SXT design is strongly coupled to gravity and temperature variations. There is a low-probability, medium criticality risk that the resulting distortions on the structure cannot be modeled with sufficient fidelity to ensure required performance verification. The risk will be mitigated by testing modules in a temperature controlled vertical facility.

### 3.1.2 Grating Technology Readiness and Development Plans

#### 3.1.2.1 Grating Technology Readiness

Requirements for the RGA were provided in Section 1.3.1.2. Its development benefits from heritage from the RGS instrument aboard XMM-Newton[27, 28, 29], which met the requirement of 2 arcsec alignments[30]. Scaling up the RGA concept requires a reduction in mass per unit interception area[31], as well as a different approach to grating mass production. Following is a discussion of both the baseline approach using traditional “in-plane” gratings, and an alternate “off-plane” concept that potentially requires fewer modules and relaxed fabrication and alignment tolerances, reducing risks while decreasing costs.

***Technology Description:*** For XMM-Newton, the RGS gratings met the flatness requirement along the optical axis by using a rib running axially along each substrate. Residual twist figure distortions were corrected by constraining the grating corners in the integrating structure. To meet the mass and throughput requirements of Constellation-X, the substrates will not feature such stiffening ribs. Instead, the thin (<0.2 g/cm$^2$) substrates will be prepared to be flat (<2 arcsec) when freestanding. The capability to produce such grating substrates in large quantities is a substantial part of the technology development plan.

A consequence of using thin, un-stiffened substrates is that the epoxy replication technique used for XMM-Newton must be replaced in favor of direct fabrication. The reason for the change in the fabrication approach is that epoxy replication imparts significant surface stresses on the substrate, which causes distortions to the optical surfaces. Using anisotropic etching of Si wafers graze-cut with respect to the (111) crystal plane, gratings have been produced (see Foldout 3-D17) that feature atomically smooth groove facets (blaze) aligned with the (111) plane. X-ray testing of these gratings confirmed a very high diffraction efficiency performance, even better than the master grating used for the RGS aboard XMM-Newton (for similar geometric parameters at 8.34Å and 13.34Å, see Foldout 3-D16). The crucial benefit of direct fabrication is neither the superior groove efficiency nor the complete bypass of the multigenerational replication process, but the fact that well understood, photolithographic and microfabrication mass-production technologies can be exploited for producing the many grating sheets required.

Because of the large number of gratings required (~1000 gratings per SXT), combined with their increased fragility, the XMM-Newton RGS alignment scheme will be too time-consuming and costly. For the RGS, a modular approach is taken in which the thin (<0.9 mm) gratings are aligned and assembled into "grating subassembly modules." These identical modules each contain approximately 10 gratings (also all identical). This highly modular approach (Foldout 3-D19) with no unique components is a key to the process. The GSE alignment fixturing disengages from the gratings after the gratings are aligned and bonded to the subassembly frame. These identical grating modules are in turn attached to the array integrating structure to assemble the full grating array (see Foldout 3-10). Attachment to the integrating structure may be done with kinematic mounts built-in to the grating module frames, or by aligning and bonding each grating subassembly to the local converging beam with the help of the CDA.

An alternate approach to the baseline utilizes high efficiency, "off-plane" gratings in place of the anisotropically etched gratings [32, 33]. In this approach, a substantially smaller number of gratings are required to build up the array, and therefore, constraints on the per-grating mass and fabrication time are relaxed. When combined with looser grating alignment tolerances, the off-plane option offers a "low-tech" solution that provides a comparable end product[34].

Aggressive technology investigations are being pursued into the "off-plane" approach concentrating on fabricating the master grating, replication gratings, fidelity studies, and arraying studies. The first test ruling procured from Jobin-Yvon was only recently delivered (December 2002) and its initial characterization is underway. A highlight of this technology program is the fabrication of a full-size, flight representative master (radial groove) grating against which replicas could be pressed. If epoxy replication proves to be a suitable technique for "off-plane" grating fabrication, most of the technology is already available and proven, reducing development risks. A parallel effort of direct fabrication for high density, off-plane gratings (at MIT's Space Nanostructures Lab) reduces risk.

Following a scheduled downselect between grating geometries, to take place at the beginning of FY04, only one of the two candidates will be considered for the flight instrument. The remainder of the discussion here will be limited to technology development for the "in-plane" (baseline) gratings.

***TRL Status:*** While gratings themselves have flown and are at TRL 8-9, the thin gratings required for Constellation-X are currently at TRL 3. Test rulings have been fabricated, verified, and X-ray tested, with extremely promising results. The test rulings have been smaller than the flight gratings and without the ruling density gradient (or chirp) required for the flight gratings (Foldout 3-D16). The path toward TRL 6, and the milestones that define those levels, is outlined in Section 3.1.2.2.

Substrate flattening was demonstrated by Magneto-Rheological Finishing (MRF) a free-standing Si wafer from an initial 14-arcsec slope distribution to 1.5 arcsec. The technology is clearly available, and methods to exploit it efficiently are under study.

The anisotropic etching process that produces super-smooth grating facets is well understood but requires tuning to work over large surfaces. A controlled interference pattern with high contrast must be set up over the entire 100 x 200 mm, and the plasma etch step must be performed over the same area. Etch facilities will be identified in industry.

Alignment fixturing for the gratings when assembled into the subassembly modules is planned to be done using microcombs[35] (also used for the SXT reflector assembly[36], see Section 3.1.1, Foldout 3-B8 and 3-D18), fabricated to 200 nm accuracy over 100 mm. Such microcombs have been fabricated, resulting in error budget contributions from the alignment tools that are small compared to other terms in the error budget.

### 3.1.2.2 Grating Technology Development Plan

***Strategy and Logic:*** Among the various technologies available to prepare and align gratings for the RGS, a few key technologies require development. These technologies are required primarily for the scaling aspects of the instrument. The deliverable gratings (~1000 per SXT) should be produced, measured, and accepted in a 2-year period, which requires a throughput of about 25 gratings per day from an industrial vendor. Since the lithographic process and anisotropic etching on the Si wafers benefit from industrial experience, technology development therefore focuses on the efficient preparation of the thin, flat, freestanding grating substrates.

***Technology Development Plan:*** The technology development to be conducted over the next two years will focus on the key areas of grating patterning, pattern replication, substrate preparation, and assembly and alignment.

First, the capability to produce flight-size gratings using scanning beam interference lithography (SBIL) will be demonstrated by making constant groove spaced gratings (December 2003). Second, the SBIL facility will be generalized to produce variable-period SBIL (VPSBIL). Availability of VPSBIL will permit "writing" a grating pattern into a full-size grating, 100 x 200 mm, in approximately one hour. A parallel fabrication approach using UV nano-imprint technology to fabricate the gratings is being pursued for risk mitigation. This approach, if usable, will provide a substantial reduction in cost, because of combined high fidelity imprinting and zero stress cure of the emulsion. This will allow patterning of substrates using a master produced with VPSBIL and will alleviate the need to write (and etch) each grating directly. After patterning, each substrate will have a reflective coating applied to complete the grating.

Several tests will be conducted on full-size gratings on flat, flight representative substrates, to verify capability to retain flatness after application of the high-density reflective coating. The surface tension of metal coatings can distort the figure of thin optics; application of the same coating on the reverse side can mitigate this effect.

Scheduled arrival dates for higher TRLs are as follows:

- TRL 4 will be reached in March 2004. The milestone is to fabricate a nearly (70%) flight size reflection grating, 140 x 100 mm with the flight specific groove facet form and ruling density. The grating will not necessarily contain the appropriate "chirp" or ruling density gradient.
- TRL 5 will be reached in September 2004. This is the critical technology milestone for grating technology development. It will be achieved when three (or more) flight representative substrates are assembled in a flight-like structure, meeting the 2 arcsec flatness criteria both for optic flatness and for mutual alignment. The substrates will be fabricated using procedures that can be applied to mass production and experience all processing steps that are included in the plan for the final flight gratings. Stiffness and resonant frequencies will be similar to the flight module frames. Verification of flatness and alignment retention before and after environmental testing will be performed.
- Capability to fabricate variable line spacing gratings will be available in mid-2005, when the VPSBIL facility upgrade is completed.
- Arrival at TRL 6 is expected in March 2006. The milestone for this will be the successful X-ray testing of an assembled grating subassembly module (approximately 10 gratings). This will be performed as an "end-to-end" test in a finite source distance, X-ray beam facility. A converging beam will be intercepted by the grating module, and the pass-through, reflected, and diffracted beams will be measured at the focal planes.

***Technology Investments to Date:*** Efforts to develop technology suitable for grating fabrication have been funded thus far by a combination of Constellation-X Technology and SR&T funding sources supplemented by leveraging DARPA activities. Results include the advances enumerated above, namely: development of the SBIL facility, capability to pattern and anisotropically etch the grating test rulings, testing the MRF substrate flattening process (at the MRF tool vendor), and holographic test ruling production for the off-plane grating concept described above. A Shack-Hartmann metrology facility was developed to provide input for the MRF flattening process. Microcomb development for grating assembly has been funded largely by the SXT group, and demonstrates the synergism in the program between the technology development efforts.

***Test Beds, Simulators, Flight Demonstrations of the Technology:*** Facilities at MIT's Space Nanostructures Lab will be used to align and assemble flat grating substrates into prototype modules. Verification of grating alignment and flatness retention will be done before and after environmental testing at either MSFC's XRCF or at Columbia's Nevis Long-beam X-ray calibration facility.

***Equipment and Facilities Required for the Technology Development Effort:*** The technology development effort will require enhancements to existing facilities already available as part of the investments to date. Included in these are the VPSBIL upgrade to the SBIL facility for writing flight size grating patterns, an ion etching tool, an upgrade of the Shack-Hartman metrology tool to provide mid-frequency resolution, and UV nanoimprint facility for mandrel production.

***Plans for Production Facilities:*** Production of flight gratings will be performed by industry, with technology transfer taking place more than a year before production commences. Routine alignment and performance verification of the modules can be performed either at MSFC's XRCF, Columbia's Nevis calibration facility, or at another suitable X-ray beam facility. A spare SXT mirror segment will be used to provide a converging beam. In the baseline approach, assembly of the grating modules into the final RGA will be performed by the FMA contractor.

#### 3.1.2.3 Key Risks and Mitigations

The key technical risks during the grating technology development phase are shown in Table 3-2.

***Meeting Substrate Requirements (RGA-1):*** The ability to produce freestanding, flat substrates of the required size.

***Flight Grating Fabrication (RGA-2):*** The ability to direct fabricate (anisotropic etch) full-size flight gratings in graze-cut Si (111) wafers.

The probability of both risks is assessed as low, however both can be mitigated by using a similar substrate production and alignment scheme as was used for the XMM-Newton RGA (TRL 8). The higher mass per grating (and integrated mass) would result in a trade between an increased mass allowance (~100%) or a reduction in grating array effective area.

### 3.1.3 CCD Technology Readiness and Development Plans

#### 3.1.3.1 CCD Technology Readiness

The RFC is an array of CCDs mounted on a common structure (Foldout 4B-12). Requirements for the RFC system are summarized in Section 1.3.1.2. The RFC consists of two separate camera systems with essentially identical requirements: the spectroscopy readout camera (SRC) and the zero order camera (ZOC). The SRC is analogous to the RFC aboard XMM-Newton[29].

***Technology Description:*** The primary features of the CCDs include high quantum detection efficiency over the 6-50Å (0.25-2 keV) bandpass, efficient rejection of stray optical light, (dark current induced) flickering pixels and non-photon background. The required readout frequency is currently ~0.5 frames per second. The other functional requirement for the CCDs is that the pulseheight spectral resolution be sufficient to separate spectral orders in small extraction regions. Back-Illuminated (BI) CCDs are required for their superior quantum detection efficiency at low energies.

The ZOC provides an attitude solution to <1 arcsec that is required to locate the wavelength scale of the SRC. Because the zero order image is undispersed, the local count-rate is higher than in the SRC CCD and therefore the readout frequency for the ZOC CCDs is moderately higher than that of the SRC CCDs.

***TRL Status:*** The CCDs are at a high TRL. The principal technology developments are enhancing from a mass production viewpoint, as the CCDs require no enabling technical development. New technology is required to improve production yield for BI-CCDs, reducing cost and schedule risks.

Heritage for the CCDs is drawn from ACIS (Chandra) and the Solid-state Imaging Spectrometer (SIS) onboard ASCA.

#### 3.1.3.2 CCD Technology Development Plan

***Strategy and Logic:*** Two technology advancements are being pursued.

- Suitable BI CCDs are currently available, but will benefit from improved production yield. To improve device yield (and as an added benefit improve low-energy efficiency), molecular beam epitaxy (MBE), a lower temperature process, will be used to thin and treat the CCD backsides.
- An unconventional, but technologically straightforward, enhancement can be made to the on-chip electronics and to the CCD analog video chain. This modification provides event driven CCD (EDCCD) capability[37]; essentially a nondestructive charge

sensor and a (CCD) serial register delay line that performs ADC conversion only when the pixels contain significant charge (see Foldout 4-B13). A conventional X-ray CCD operates by reading out the full array, and pattern recognizing the X-ray events contained in each digitized frame, though >99% of the pixels typically contain no X-ray events. By converting only the pixels containing charge detectable by the nondestructive sensor, an enormous savings is made in the energy consumption per frame readout. With a fixed power budget, a larger readout frequency may be attained in exchange for the reduced energy per readout. The current estimate of the frame readout frequency is over 10 Hz. While not a requirement for the RFC, this enhancement will vastly improve data quality, timing resolution, and background rejection for the RGS system.

***Technology Development Plan:*** The roadmap for technology development of the MBE-BI EDCCDs includes several iterations of fabrication, packaging, tuning, and testing. Each iteration is done in "half lots" to reduce costs. The fabrication and packaging are performed at MIT/LL, while the testing is performed at MIT/CSR. The first EDCCDs (Gen.1, Lot1), were fabricated and packaged in September 2002. They feature the EDCCD on-chip electronics included in a front-illuminated (FI) device. Gen.1, Lot1 CCDs will suffice to test the predicted EDCCD power savings and assess radiation damage performance. Radiation damage testing should be complete by March 2003.

Mask design and layout for the Gen.2 Lot1 devices (including the MBE processing) began in October 2002, and their testing (quantum efficiency, resolution, background rejection, radiation damage, etc., is due for completion in October 2003. At that point, TRL 4 will be reached for the grating spectrometer EDCCDs.

Production of Gen.2 Lots 2 and 3 will start in October 2003 and October 2004, respectively, during which optimization of the MBE processed backside and optical blocking filter application will be performed. TRL 5 is scheduled for March 2005, when an engineering unit focal plane is produced, with camera electronics including field programmable gate arrays (FPGAs). TRL 6 will be reached in September 2005 following environmental testing of the prototype focal plane.

***Technology Investments to Date:*** Technology development for BI-EDCCDs has been funded by a combination of Constellation-X technology and SR&T funding sources. In addition, the first "event drive" circuitry on a functional (frontside illuminated) Gen-1 EDCCD was produced as a piggy-back in production for the XIS CCDs on Astro-E2 (see Foldout 4-B14).

***Test Beds, Simulators, Flight Demonstrations of the Technology:*** Gen-1 EDCCDs provide a test bed for the "event drive" concept for CCD readouts. These tests will demonstrate EDCCD technology and functionality. MBE BI CCD test devices will be produced to verify charge collection performance for the flight devices.

***Equipment and Facilities Required for the Technology Development Effort:*** Fabrication and packaging of the test lots of CCDs will be done at existing facilities (MIT/Lincoln Labs), while GSE, including electronics and calibration facilities, will be fabricated for EDCCD testing and calibration at MIT.

***Plans for Production Facilities:*** Plans for producing the RFCs include use of both commercial and institutional facilities. EDCCDs can be produced, tested, and screened in commercial settings. Integration and testing of the RFC system can be done either by an industrial vendor or at an academic institution.

#### 3.1.3.3 Key Risks and Mitigations

The key technical risks during the CCD technology development phase are shown in Table 3-2.

***Low MBE CCD Yield (CCD-1):*** To mitigate the risk of a low BI-MBE CCD yield, other low-temperature backside preparation processes will be considered, as well as procurement of back-illuminated X-ray CCDs from alternate vendors (e.g., EEV).

***EDCCD Circuitry Design (CCD-2):*** In the case that the event driven circuitry design is not demonstrated, the mitigation will be to not use the (optional) circuitry. The EDCCD then functions as a normal CCD.

### 3.1.4 X-ray Microcalorimeter Technology Readiness and Development Plans

#### 3.1.4.1 Microcalorimeter Technology Readiness

***Technology Description:*** The XMS is a high-quantum-efficiency, imaging spectrometer with 4-eV resolution near 6 keV, 2-eV resolution near 1 keV, and the ability to function at count rates up to 1000 counts/sec/pixel. In order to meet the design requirements of efficiency and spectral resolution, a low-temperature detector must be used. Within this class of instruments, only microcalorimeters with resistive temperature sensors are sufficiently developed for the Constellation-X technology roadmap. Superconducting transition-edge sensor (TES) microcalorimeters are in development for the XMS baseline, and semiconductor thermistor microcalorimeters (specifically, neutron transmutation doped [NTD] Ge) as an alternate implementation[38].

***TRL Status:*** At the start of the technology development effort in 1998, TES and semiconductor microcalorimeters were at TRL 3, relative to the needs of Constellation-X. This is an important clarification, as both technologies at that time were ready for less demanding applications[39]. For Constellation-X, demonstrations of fewer-pixel, lower-resolution (6 eV), and/or slower (3 msec) microcalorimeter arrays (i.e., similar to those on Astro-E2), coupled with theoretical estimates of improved performance, constitute experimental and analytical proof-of-concept, hence, TRL 3. Many component technologies, such as schemes for close-packing the XMS pixels and integrating their X-ray absorbers, were at TRL 1 at the onset, and are now at TRL 3 or higher. TES technology is presently at TRL 4 because small TES arrays (5 x 5) with pixels of size, quantum efficiency, and fill factor suitable for XMS have been demonstrated. The readout scheme also has reached TRL 4 through a recent demonstration of 2 x 12 multiplexing of TES devices on 4 separate chips, including two 8 x 8 arrays.

#### 3.1.4.2 Microcalorimeter Technology Development Plan

***Strategy and Logic:*** The rapid progress in TES technology, the theoretical prediction of 2 eV resolution and the potential for large scale multiplexing with supeconducting read-out combined to recommend TES development for the XMS baseline. To mitigate risks associated with a relatively new technology, the more traditional semiconductor-based microcalorimeter technology at SAO is developed in parallel. Such NTD calorimeters have attained energy resolution of 4.8 eV at 6 keV[19].

***Technology Development Plan:*** The microcalorimeter XMS technology roadmap is shown in Table 3-4. At the beginning of the development, a very high energy resolution was obtained (e.g., 2.0 eV at 1.5 keV[40], and 4.5 eV at 5.9 keV[41]), in large, isolated TES pixels using proximity-effect bilayers (Mo/Cu and Mo/Au) on much larger silicon nitride membranes which provided the necessary thermal isolation of the TES from the 50 mK heat sink. These early devices were individual 6-mm square chips with central active areas of 0.3 to 0.6 $mm^2$. To meet the XMS pixel size requirement the following enabling component technologies have been pursued. (1) Compact pixels consisting of a 0.15 x 0.15 mm TES surrounded by a ~10 μm wide silicon-nitride perimeter, as shown in Figure 3-2, have been developed. The thermal conductance of this thermal link is tuned through perforating the nitride and/or choice of the nitride thickness[42]. (2) Bi/Cu mushroom-shaped X-ray absorbers (0.24 x 0.24 mm) that contact the TES in the middle but are cantilevered over the nitride

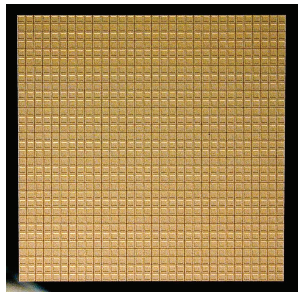
**Table 3-4:** Microcalorimeter Technology Roadmap

| Element | Array TRL 4 | Readout TRL 4 | TRL 5 | TRL 6 | Flight Baseline |
|---|---|---|---|---|---|
| Array size | 5 x 5 | 24 assorted pixels on 4 chips | 8 x 8 | 32 x 32 | 32 x 32 |
| Channels simultaneous readout | 2 | 24 | 16 | 96 | 1024 |
| MUX scale | None | 2 x 12 | 2 x 8 | 3 x 32 goal | 32 x 32 goal |
| Pixel size | 0.25 | 0.4 | 0.25 | 0.25 | 0.25 |
| Timescale | Q1 of FY03 | Q1 of FY03 | Q4 of FY04 | Q4 of FY05 | |

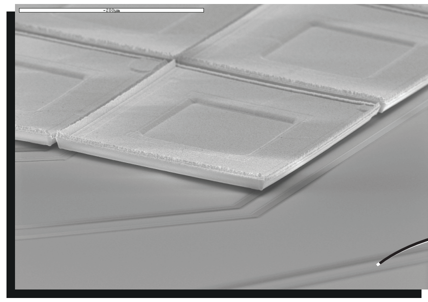
# Constellation-X Focal Plane Module Instrument Technologies

## A X-ray Microcalorimeter Spectrometer (XMS)

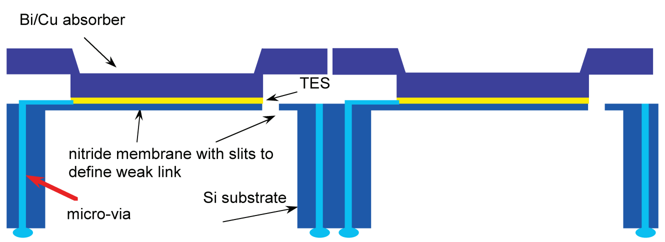
### Microcalorimeter Array



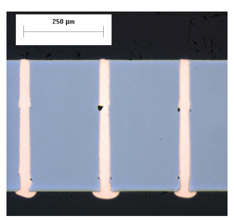
1) Top View of full 32 x 32 array of Bi/Cu X-ray absorbers.



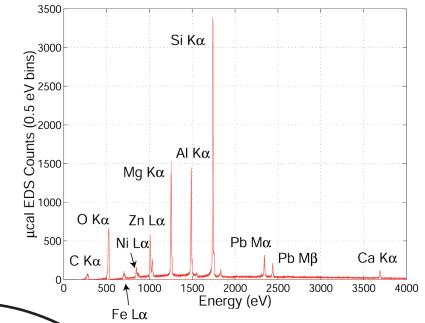
2) SEM angled view showing 240 µm canti-levered absorbers on a fully-integrated array.



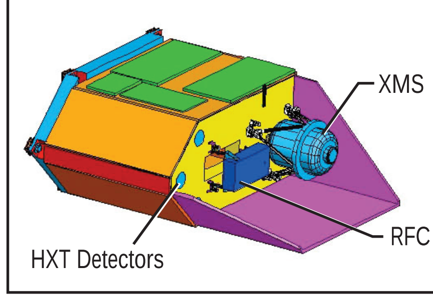

3) Concept for high-density array of X-ray microcalorimeters using overhanging absorbers and micro-via interconnects.

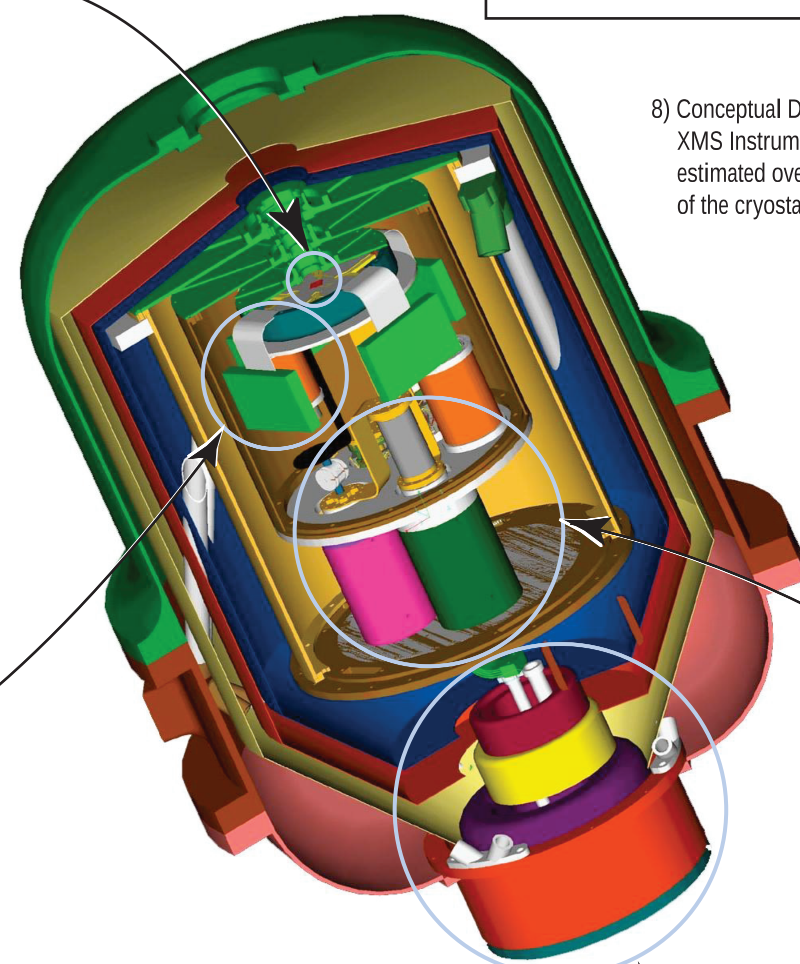


4) Cross-section of prototype Cu-in-Si micro-via interconnect prototype. The vias are 425 x 25 µm.



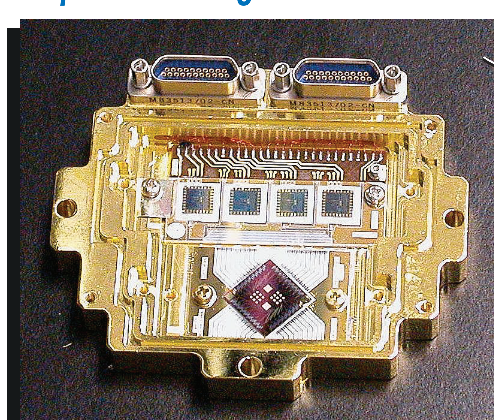

7) High Resolution X-ray spectrum obtained with a superconducting microcalorimeter.



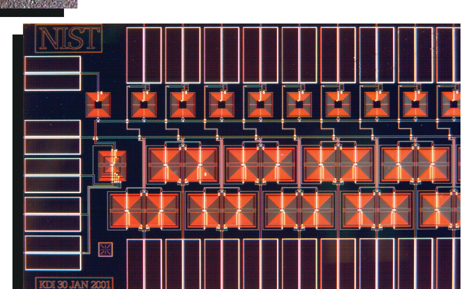



8) Conceptual Design of the XMS Instrument. The estimated overall dimensions of the cryostat are 50 x 75 cm.

### Superconducting Readout

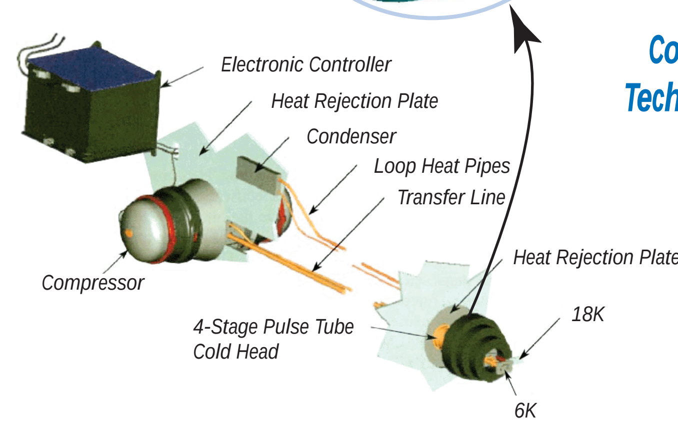


5) Four-channel test platform showing microcalorimeter arrays and first stage superconducting preamplifiers.

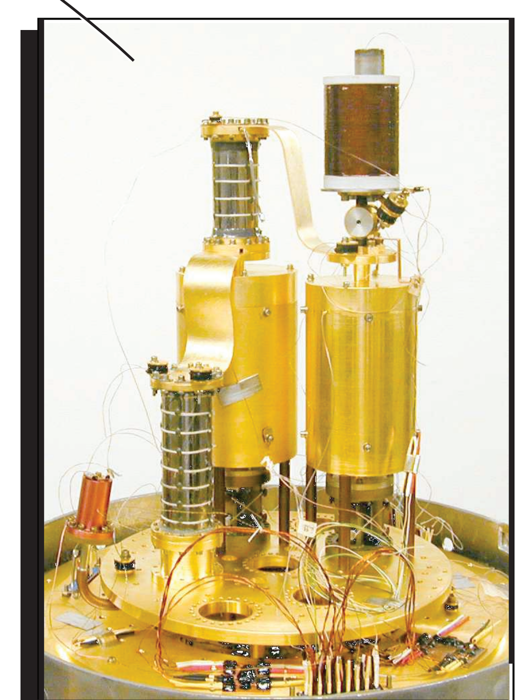



6) Portion of 32 channel superconducting multiplexer chip for low-power readout of microcalorimeter array.

### Cooling Technology

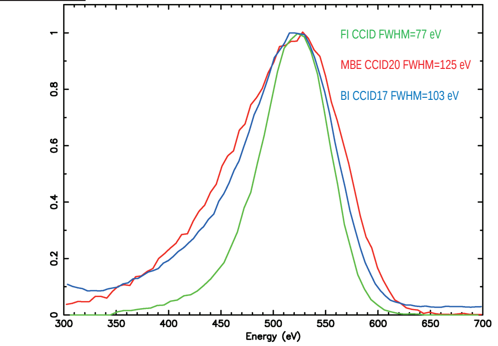



9) Lockheed Martin 6K cryocooler design from Advanced Cryocooler Technology Development Program (ACTDP).

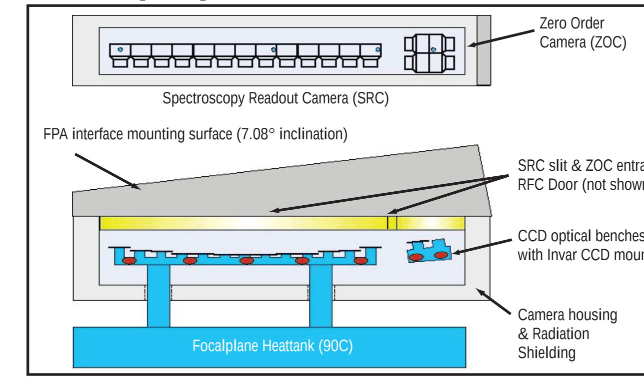


10) Four-stage 50 mK continuous adiabatic demagnetization refrigerator (CADR) in test dewar.

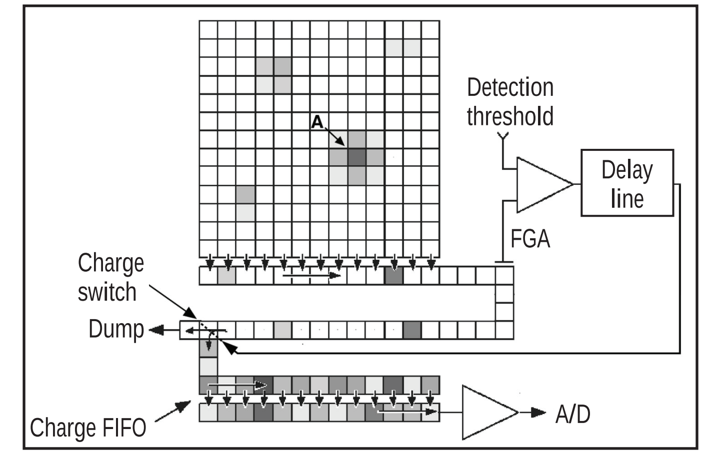
## B Reflecting Grating Focal Plane Camera (RFC)




11) Energy Resolution of MBE is already comparable to best previous back-illuminated CCD.



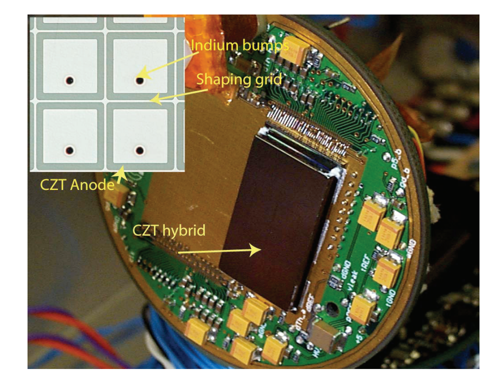

12) Concept for RGS Focal Plane Camera (RFC).



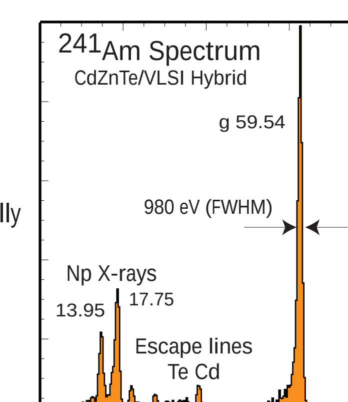

13) Event-driven CCD schematic.

14) Generation 1 Event-Driven (frontside illuminated) CCD featuring EDCCD "event drive" electronics on each of four readout nodes (nondestructive charge sensor, analog delay line, charge dump, charge FIFO and ADC).

## C Hard X-ray Telescope (HXT) Detector




15) Prototype hybrid CdZnTe detector mounted to the readout board. Two sensors placed side-by-side make up the 2.6 x 2.6 cm focal plane. (Inset): CdZnTe anode with shaping grid and indium interconnect bumps.




16) Spectrum of a $^{241}$Am source fully illuminating a pixel of a HEFT detector operated at 18° C.

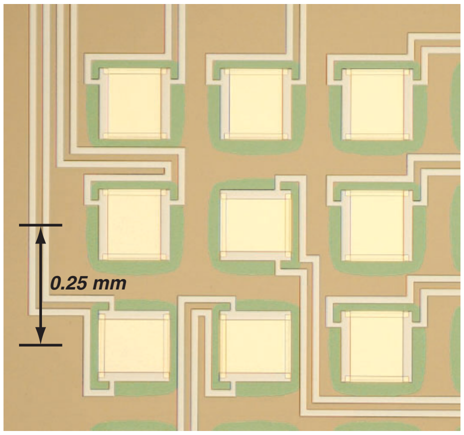



**Figure 3-2:** Portion of Mo/Au TES array. 0.25 mm spacing meets the XMS requirement.

border and wiring channel for maximal fill factor have been developed[43]. Both of these component technologies have been successfully demonstrated, and refinements are continuing. Spectral resolution of 2.5 eV at 1.5 keV has been demonstrated in a compact pixel without an absorber, and in the first array of compact pixels with integrated overhanging absorbers (Foldout 4-A3) 10 eV resolution has already been achieved. The performance of this device was limited mainly by parasitic resistances in the electrical contact traces. To extend these arraying concepts to 32 x 32, a further enabling component technology is needed: (3) high density array interconnects. Two approaches are being pursued to bring the electrical contacts to each pixel in a 1024-pixel array. In one, ultra-low-resistance micro-vias bring the signals out to the back of the array, where they can be bump-bonded to a fan-out board. This scheme, along with the Bi/Cu absorbers, is illustrated in Foldout 4-A3 and 4-A2. In the other, surface micromachining is used to fabricate calorimeter pixels that stand above a solid substrate, leaving the space under each pixel available for wiring tracks.

Another critical area of development has been in the superconducting read-out electronics. The resistance change in each TES is sensed by measuring the change in current in its bias circuit with a SQUID. To meet the bandwidth requirements, series-array SQUIDs must be used as one stage of the current amplification. Although a 32 x 32 TES microcalorimeter array can be read out using 1024 independent channels of electronics, reducing the number of channels through use of a SQUID multiplexer (MUX)[44] significantly reduces the heat load on the ADR, and the complexity of the front-end assembly. A time-division multiplexing scheme in which each 32-pixel column is read by one series-array SQUID is in development. Each TES pixel is sampled by its own input SQUID, which is switched on and off by the MUX controller. Figure 3-3 is a schematic of the MUX read-out. A successful demonstration of 2 x 12 multiplexed X-ray TES devices in a test at NIST has just been completed. Initial studies to quantify the performance have indicated no statistically significant degradation in resolution as the number of MUXed channels is increased.

Particle rejection for XMS is required to flag as background events those signal pulses that result from energy deposition by cosmic rays. The baseline scheme is based on detectors designed for detection of dark matter particles, and Stanford University will be funded to pursue this application of their Cryogenic Dark Matter Search (CDMS) technology. Such a detector would consist of a Ge crystal with TES sensors on its surface. The energy resolution requirement for the anti-coincidence detector is set by the required threshold energy. This will be determined after modeling the response to the expected cosmic ray environment at L2. Leveraging heavily off of the CDMS technology[17] makes the anti-coincidence detector a much more modest development effort than the spectroscopy array.

***Test Beds and Simulators:*** These key component technologies will be integrated in separate TRL 5 and TRL 6 system demonstrations. For the TRL 5 demonstration, a 2 x 8 SQUID MUX system will be used to read out a portion of an 8 x 8 array. High density array interconnects will not be needed at this point. For the TRL 6 demonstration, a 3 x 32 SQUID MUX system will be used to read out a portion of a 32 x 32 array. The engineering model will be based on the TRL 6 demonstration unit, redesigned to meet the requirements on mass, thermal loads, and mechanical robustness. The power required per channel will be the same in the flight model as in the TRL 6 demo unit. Table 3-4 summarizes the technology roadmap.

***Equipment and Facilities:*** Key facilities needed for the primary development effort already exist at the microfabrication laboratories at

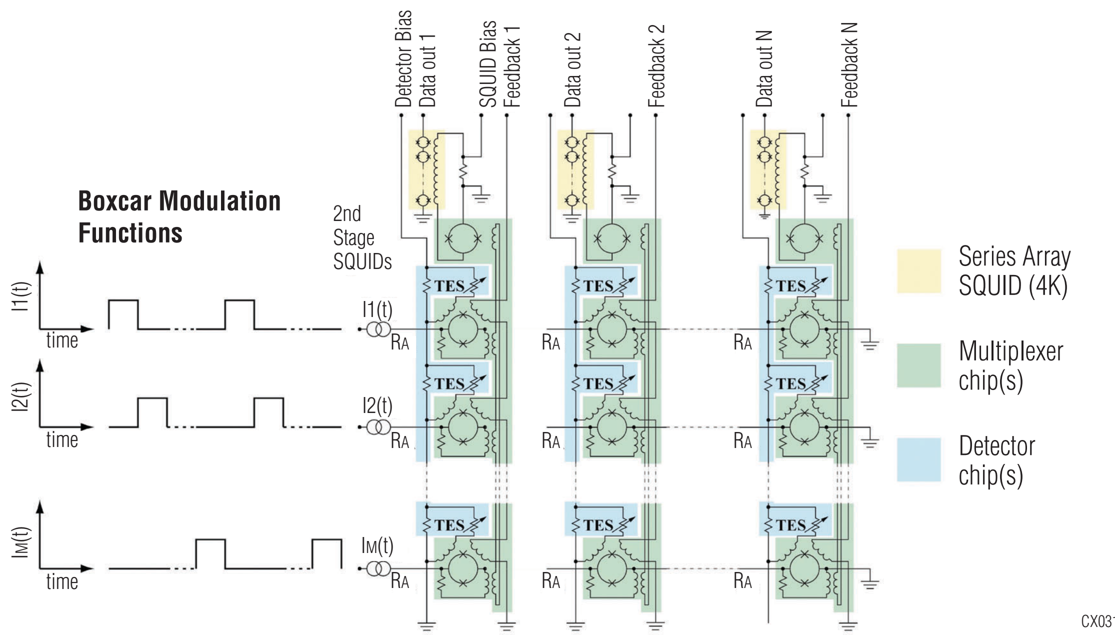



**Figure 3-3:** Schematic of SQUID MUX Readout

GSFC and NIST-Boulder. There are cryogenic test platforms at both institutions.

The GSFC Detector Development Lab (DDL) has sophisticated fabrication facilities including systems for photo-lithography and e-beam lithography, a 1 MeV ion implanter, several standard deep reactive ion etch (RIE) systems, and several sputtering and e-beam thin film deposition systems. A flip-chip bonder will be added in the next month. Process development and fabrication of TES arrays, high-density interconnects, and superconducting fan-outs will continue to be carried out in this facility. The NIST superconducting microfabrication facility is used for the fabrication of complex superconducting integrated circuits, including the Josephson voltage standard. Systems are available for photolithography, e-beam lithography, thin film deposition, and etching. Process development and fabrication of single SQUIDs, SQUID multiplexers, SQUID series arrays, and TES devices will continue to be carried out in this facility.

Both the NIST and GSFC calorimeter groups already have many cold test platforms for testing components and systems, including two dilution refrigerators and multiple adiabatic demagnetization refrigerators.

#### 3.1.4.3 Key Risks and Mitigation

The key technical risks during the XMS technology development phase are shown in Table 3-2.

***TES Detector Fabrication (XMS-1):*** The low-probability risk of not meeting the 4 eV resolution requirement during the technology development phase is mitigated in three ways: (1) developing the TES detector fabrication in two independent laboratories, (2) developing in parallel the NTD/Ge semiconductor detector, and (3) via ongoing development of TES technology by independent international groups who make their results available to the Constellation-X Program.

***High Density Array Interconnects (XMS-2):*** The low-probability risk is mitigated by developing parallel approaches (micro-vias and surface micro machining) to development. A third alternative utilizing stacked insulated leads is also available if required. For the NTD case, the arrays are assembled from individual rows of devices with vertical fanout substrates[45]. This trades the complexity of the interconnects with the complexity of micro-assembly and is considered a low risk approach.

***SQUID MUX Speed and Noise (XMS-3):*** The low-probability risk in developing a SQUID MUX system with adequate speed and noise performance is mitigated by trading the number of MUXed channels against heat load and design complexity. There exists a region of phase space in which the scale of the multiplexing can be traded against the thermal loads on the ADR without impacting instrument performance. Beyond that, the cost in performance results in increased dead time at a particular count rate, and not in degraded spectral resolution. Given current state-of-the-art, a MUX scale of 32 x 32 with detector fall times as fast as 0.5 ms should be achievable, with a realistic goal for 0.1 ms fall times.

### 3.1.5 ADR Technology Readiness and Development Plan

#### 3.1.5.1 ADR Technology Readiness

***Technology Description:*** The XMS detector assembly will be cooled to 50 mK using a "continuous" adiabatic demagnetization refrigerator (CADR; see Figure 3-4). This system is capable of meeting the detector cooling power requirement (6 microwatts at 50 mK) and of rejecting heat at controlled rates to a mechanical cryocooler (<20 mW at 6 K). It is based on conventional (i.e., single-shot) ADR technology but operated in a fundamentally different manner that dramatically increases its cooling power per unit mass and reduces its peak heat rejection rate.

Conventional ADRs use a discrete process in which the refrigerant is first magnetized (warming it up and allowing heat to be rejected to a heat sink), and then demagnetized to cool to low temperature. This simple single-shot technique is extremely robust and is easily implemented in space-flight instruments. The Astro-E/E2 missions use this approach.

Single-shot operation, however, is limited to heat rejection in short bursts at widely spaced intervals. An ADR sized to meet XMS cooling requirements needs to reject heat at rates far exceeding the capability of cryocoolers presently under development for the Advanced Cryocooler Technology Development Program (ACTDP). Also, because a single-shot ADR must store heat for extended periods of time, the relatively low entropy density of magnetic refrigerants translates to large system size and mass.

The CADR under development eliminates both of these problems. It uses multiple stages arranged sequentially (Figure 3-4), with each salt pill connected to the next stage (or to the heat sink) by a heat switch. The first stage acts as a heat capacity reservoir to regulate the temperature of the detectors, while the other stages cascade heat to the cryocooler. Four stages are required to produce continuous cooling at 50 mK using a 6 K heat sink. A fifth stage will be used to regulate the detector's second-stage SQUIDs at 1 K.

***TRL Status:*** The CADR development began in 1999 with a TRL 3 demonstration of heat transfer between two stages at low temperature (50 mK). In the last two years, with funding from NASA's CETDP, the technology reached TRL 4 with the demonstration of a four-stage breadboard CADR (with nonmoving parts) operating continuously at 50 mK using a 4.2 K heat sink. Its cooling power (6 microwatts at 50 mK) and peak heat rejection rate (≤7.5 mW to 4.2 K) exceed the Constellation-X requirements. The present focus is on testing a new fourth stage that incorporates a gadolinium fluoride refrigerant that will increase its heat rejection capability into the 6K range, as required by the ACTDP coolers.

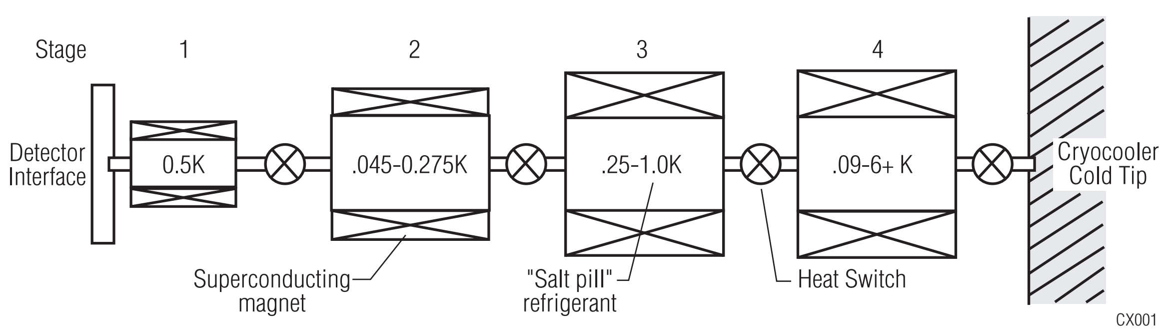



**Figure 3-4:** Block Diagram of 4-Stage CADR Demonstration Units

#### 3.1.5.2 ADR Technology Development Plan

***Strategy and Logic:*** The development strategy was to first demonstrate the components and heat transfer processes needed for continuous cooling at very low temperatures, then to develop the upper stages needed to reject heat at high temperatures. The initial focus was therefore to develop low temperature heat switches and salt pills, and to build a 2-stage demonstration unit. This was a critical step since the system's thermodynamic efficiency and heat transfer rates established the performance requirements for the upper stages. As these were produced, the 2-stage assembly was expanded to three and then to four stages, which at present has a heat rejection capability of 4.2 K. Through this process, all of the heat switches, salt pills, and control software, and some suspension components, have now been fully demonstrated, and the breadboard CADR is close to fully optimized.

***Technology Development Plan:*** The plan for taking this technology to TRL 6 involves three main thrusts.

- Continue development of the fourth and fifth stages. This includes continued engineering of refrigerant materials with better entropy density and lower magnetic field requirements to meet the 6 K heat rejection requirement, and the fabrication of a stage to demonstrate continuous cooling at 1 K.
- Development of high-temperature magnets. The CADR's magnets (in stages 2-5) will be cooled to 6K by the cryocooler. This temperature is just beyond the practical limit for using NbTi technology. Although higher temperature superconductors like Nb3Sn will work at temperatures up to 12K, wire manufacturers do not produce the small gauge wire needed for high field, low current magnets. The plan is to begin funding industry partners that have expertise in this area. In particular, a new technique being pioneered by Superconducting Systems, Inc., for producing very fine Nb3Sn wire that can be reacted before being wound into magnets looks very promising.
- Assemble and flight-qualify a 5-stage engineering unit CADR that meets the XMS's cooling requirements. The emphasis will be on developing suspension systems that provide structural support to the low temperature components, while not degrading the CADR's thermal performance.

The development schedule aims to have this system ready for full functional testing with the prototype ACTDP cryocooler in FY06.

***Test beds and Simulators:*** The Cryogenics and Fluids Group has a long history of developing flight ADRs, and has extensive facilities for testing ADR components and assemblies. These include several helium dewars and one cooled by a commercial pulse-tube cryocooler. These are modular and adaptable systems that will accommodate virtually any final CADR configuration. The latter will be particularly valuable as a high-fidelity simulator for the Constellation-X cryocooler's interface. Existing vibratable dewars are available for cold vibration of components and assemblies.

As part of the on-going CADR development effort, the GSFC Cryogenics Group has developed high-fidelity ADR simulators to model the performance of multi-stage systems. The simulators show excellent agreement with as-built components, and will be used to optimize the design of the 5-stage engineering unit CADR prior to beginning fabrication.

***Equipment and Facilities:*** The Cryogenics Group has many unique facilities for producing and testing flight ADR systems, including a state-of-the-art wire electric discharge machine (EDM), equipment for growing hydrated salts, a coil winder for superconducting magnets, and an apparatus for characterizing the entropy of magnetic refrigerants. These facilities have been critical for prototyping of components for the CADR development, and will be available for production of the flight instruments.

#### 3.1.5.3 Key Risks and Mitigation

The key technical risks being addressed during the XMS ADR technology development phase are shown in Table 3-2.

***CADR Thermal Interface Requirements [XMS-4]:*** The ACTDP cryocoolers are required to provide a base temperature of 6K or below, with a cooling power of 20 mW or higher. The CADR already meets the cooling power requirement, but has not yet demonstrated magnet operation at 6K. In the event that higher temperature magnet technology does not mature in time for Constellation-X, it will be necessary to reduce the operating temperature of the cooler. Partially for this reason, the solicitation for

ACTDP cryocoolers specified a goal of 4 K operation. The trade off may be a reduction in cooling power, but likely not to a degree that would impact the operation of the CADR. However, if it were necessary, the CADR could be reconfigured to significantly reduce its cooling power requirements.

***SQUID Magnetic Field Noise [XMS-5]:*** There is a potential for fringing magnetic fields to interfere with the XMS detectors and SQUID amplifiers. Two strategies are used to minimize magnetic interactions between the CADR and the XMS: (1) ferromagnetic shielding around each of the CADR's magnets provides a high degree of attenuation of fringing fields. (2) the detector assembly is physically located as far as possible from the largest magnets. It has already been verified that fields in the vicinity of the detectors will be less than 1 mT. This is well below the levels of concern, and can be totally eliminated by passive and/or superconducting shielding around the detector assembly.

### 3.1.6 Cryocooler Technology Readiness and Development Plans

#### 3.1.6.1 Cryocooler Technology Readiness

***Technology Description:*** A key component of the XMS is a mechanical cryocooler that provides several stages of active cooling inside the instrument cryostat. Its primary purpose is to provide a 6 K heat-sink stage for the ADR described in Section 3.1.5. A secondary purpose is to actively cool a stage at the 90-100 K "warm" end of high temperature superconducting ADR power leads. A tertiary requirement is for heat-sink stages intermediate to those just mentioned. All stages include actively cooled radiation shields, several of which also connect to infrared blocking filters in the optical path.

***TRL Status:*** The space cryogenics community is transitioning from stored cryogen systems to ones incorporating mechanical cryocoolers. Several cryocooler systems employing different technologies and capable of reaching 50 K are currently at TRL 9. Cryocoolers reaching as low as 15 K exist at the TRL 5 level. Cooling to around 6 K has been achieved in the laboratory, qualifying that technology for the TRL 4 category.

#### 3.1.6.2 Cryocooler Technology Development Plan

***Strategy and Logic:*** Development of a cryocooler to meet the needs of Constellation-X is part of a cooperative effort within NASA's OSS. Through the JPL-managed Navigator Program and the Terrestrial Planet Finder project (TPF), OSS is funding the ACTDP. The primary users of ACTDP technologies will be NASA's Constellation-X, JWST, and TPF missions. The goal is to develop several technologies that can yield a demonstrable cryocooler design capable of realistically completing flight unit delivery in the 2007 time frame.

Members of the Constellation-X team are actively participating in the ACTDP as members of the Technical Peer Review Panel and the Programmatic Review Panel. Project involvement will increase as one of the ACTDP coolers is driven to become the TRL 6 engineering model cryocooler for Constellation-X.

***Technology Development Plan:*** The ACTDP is divided into a Study Phase and a Demonstration Phase. The Study Phase of the program is complete and contract negotiations with three contractors for the Demonstration Phase are in progress. During the first year of that phase, each contractor will have individualized development tasks designed to retire specific technological risks identified by the ACTDP Technical Peer Review Panel. Successful completion of those tasks will lead to contract options for construction and testing of TRL 5 cryocoolers. It is expected that the transition of the cryocooler from TRL 5 to TRL 6 will be managed by the XMS IPT lead.

***Test Beds and Simulators:*** All test beds required for the development of the TRL 5 cooler are budgeted for under the ACTDP. It is expected that these will be available for TRL 6 qualifications under Constellation-X funding. A mass model of the final cryocooler coldhead design will be required for inclusion in cryostat integration and vibration testing.

***Equipment and Facilities:*** The contractors selected under the ACTDP have in-house facilities and equipment adequate to develop the cryocoolers through TRL 5. No additional specialized facilities nor equipment are required to transition from TRL 5 to 6.

#### 3.1.6.3 Key Risks and Mitigation

The key technical risk during the development phase is shown in Table 3-2.

***Achieving Required Cryocooler Cooling Efficiency [XMS-6]:*** Although the proposed ACTDP cryocoolers were primarily designed with existing technologies, there remain risks associated with the cryocooler as a system. The ACTDP technical panel identified risk items for each cryocooler in the areas of technology development, manufacturing and overall cooling efficiency. The first stage of risk mitigation is within the ACTDP itself. The approach is to contract with the three remaining vendors for one year of development directed individually toward retirement of identified risks. Contract options will then be exercised for vendors succeeding during that period.

Constellation-X is base-lining the pulse tube cooler being designed by Lockheed-Martin (LM) under the ACTDP for its applicability to the XMS system. Should LM have difficulties in retiring its risks over the next year, the project would initiate a second-stage of risk mitigation with one or both of the other ACTDP contractors, and fund an accommodation study of another ACTDP technology would be required. A third stage of risk mitigation could be considered a case where Constellation-X required the hardware of an ACTDP vendor other than LM.

The fourth mitigation stage would be the use of a hybrid cryocooler/stored-cryogen system with an inner radiation shield of the cryostat cooled by an existing 35 K cryocooler. Such TRL 6-7 cryocoolers have the heritage of the 50 K flight coolers being used on Atmospheric Infrared Sounder (AIRS) and Tropospheric Emission Spectrometer (TES). Achieving the mission science requirements with this approach will incur a mass penalty, as well as possible cost and schedule penalties.

### 3.1.7 Hard X-ray Telescope Mirror Technology Readiness and Development Plans

#### 3.1.7.1 HXT Mirror Technology Readiness

The HXT mirror requirements are described in Section 1.3.1.4. An individual HXT mirror module must have an angular resolution <1 arcmin HPD, an effective area of >1500 $cm^2$ from 6-40 keV, and an 8 arcmin FOV across this energy band. Each satellite carries three co-aligned HXT telescope modules each with 10 m focal length, whose mass must not exceed 150 kg.

***Technology Description:*** The HXT technical approach is based on depth-graded multilayer-coated conical approximation or Wolter-I optics. The optics are high-throughput, low mass, and highly nested, smooth (RMS <0.4 nm), and have a thin film of alternating high and low index of refraction materials (multilayer) applied. The multilayer films typically have 100-300 layer pairs of Tungsten and Silicon, with bilayer thicknesses ranging from 20- 200 Å.

Two optics approaches are being considered: nickel and glass (see Table 3-5). In the former, each shell is an integral unit, while in the latter, each shell is assembled from a number of segments. The integral nature of the Ni shells gives them the advantage of mechanical integrity, with fewer pieces requiring precision alignment. The primary disadvantage of integral shells is that the multilayer coatings are more difficult to apply, and the estimated mass will be 30% larger. For integral shells, the multilayers must either be applied to the interior surfaces or must be replicated from the same mandrel as the shell. The former is not easily done with standard magnetron sputtering systems (the technique of choice for growing large-areas of smooth, thin films), and the latter requires development in more complex steps in the replication process, including appropriate release layers. In contrast, application of high-quality multilayers of design applicable to the HXT has already been demonstrated for segmented shells.

***TRL Status:*** The general approach of segmented conical optics has been demonstrated in flight on BBXRT, ASCA, and Astro-E and InFOCμS balloon payloads. The thermally

**Table 3-5:** Nickel vs. Glass Mirror Dimensions

| | Segmented | Integral |
|---|---|---|
| Substrate | Thermally formed Glass | Electroformed Nickel |
| Thickness | 0.2 – 0.3 mm | 0.1 – 0.15 mm |
| Shells/module | 150 | 82 |
| Inner radius | 4 cm | 6 cm |
| Outer radius | 20 cm | 20 cm |
| Mass target/ satellite | 95 kg | 150 kg |

formed glass development draws largely from the HEFT balloon experiment, which has developed substrates, multilayer coatings, and substrate mounting technique, all of which have now demonstrated the HXT performance requirements, except on the smallest radius shells. Glass optics fabricated for HEFT achieve 45 arcsec HPD resolution for shell radii greater than 10 cm (see Foldout 3-C14). Epoxy replication of the substrates (as described in Section 1.3.1.4) is being pursued to improve the figure on small radius shells. Glass substrate production benefits from the SXT mirror technology development, as SXT reflectors exceed the HXT figure requirement, overlap between the HXT and SXT fabrication approaches offers potential economies during implementation. Depth graded multilayers of the HXT design have been applied to formed substrates, and the required reflectance has been demonstrated (see Foldout 3-C13). Multilayers replicated onto glass substrates show comparable X-ray efficiencies.

Nickel replica mirrors with the requisite resolution and similar dimensions to the HXT were demonstrated in flight on XMM-Newton. Substrates of requisite thickness have been produced and tested as part of the HERO balloon experiment. Depth-graded multilayers with the required reflectance have been fabricated, but the application to nickel shells either through deposition onto a mandrel and subsequent replication onto the mirror, or through direct application using a specialized coating system needs to be demonstrated.

Based on the above discussion, the glass mirrors are at TRL 4-5, while the component technologies are at TRL 5-6. The nickel optics are at TRL 3, with the component technologies at TRL 4 (multilayers) and TRL 6 (Ni shells).

### 3.1.7.2 HXT Mirror Technology Development Plan

***Strategy and Logic:*** Both HXT mirror approaches have already demonstrated technologies at the component level. A parallel development track is followed as late as possible into the program. Small prototypes of Ni and glass mirrors are being constructed for performance evaluations. One technology will then be selected in FY03 to proceed to a full prototype for both performance and environmental testing. Technology selection includes consideration of the production processes capable of meeting the required volume of reflectors.

***Technology Development Plan:*** The HXT mirror technology development steps are outlined below:

1. Fabricate nickel and glass prototypes for demonstration/performance comparison.
2. Test prototypes at MSFC for X-ray reflectance, and angular resolution. (TRL 4)
3. Fabricate prototype with full range of mirror shell dimensions and flight-design multilayers. (TRL 5)
4. Evaluate X-ray reflectance, throughput, and angular resolution.
5. Test full prototype for vibration tolerance and thermal tolerance. (TRL 6)

***Technology Investments to Date:*** Most of the HXT mirror technology is leveraged from NASA SR&T programs. For the HXT program, this has supported the development of glass mounting schemes, glass shell production, and prototypes at Columbia University, completion of a multilayer deposition facility for shell mirrors at SAO, comparative studies of candidate multilayers by SAO, and development of mandrels for prototype shells and segment product, by MSFC and GSFC, respectively.

***Test Beds and Simulators:*** The small prototypes under development serve as test beds for the two approaches to the optics technologies. The facilities listed below serve as a test beds for mirror fabrication, coatings, and alignment.

***Equipment and Facilities for Technology Development:*** The HXT mirror program takes advantage of facilities developed for other programs. The glass mirrors utilize facilities developed for HEFT, including metrology stations developed at Columbia, mounting and alignment fixtures developed at Colorado Precision Products, Inc., a multilayer deposition chamber at the Danish Space Research Institute (Foldout 3-C12). Also utilized, are the glass forming and replication facilities at GSFC developed for the SXT mirror. The Ni mirrors utilize the mandrel machining facilities at OAB, Ni electroforming facilities at MSFC, and a multilayer deposition chamber at SAO. The later two facilities were developed in part with Constellation-X funding. Both mirror approaches will use the MSFC X-ray calibration facilities.

***Plans for Production Facility:*** As for the SXT, the HXT mirror production facilities can be modeled after existing and previous production efforts. The glass mirror production and coatings can be based on the GSFC facility that produced the InFOCμs mirror, along with the Astro-E/E2 mirrors. A Ni mirror facility can be modeled after the Media-Lario facility used for XM, or the MSFC facility used for HERO. A reasonable option for the glass mirror option is to set up the HXT production as a parallel line in the SXT production facility to accommodate the glass forming; multilayer deposition would require a separate facility.

### 3.1.8 HXT Detector Technology Readiness and Development Plans

#### 3.1.8.1 HXT Detector Technology Readiness

The HXT focal plane performance requirements and physical detector requirements are described in Section 1.3.1.4. The detector must operate over the 6-40 keV band with better than 90% quantum efficiency, with a threshold at 6 keV, and with a resolving power of 5 (DE/E = 20%). In addition, the background must be low enough to guarantee that signal dominates noise for a $10^5$ s observation. Each satellite carries three co-aligned telescopes with independent focal planes consisting of a solid state pixel sensor surrounded by an active shield.

***Technology Description:*** The baseline option for the Constellation-X HXT focal plane detectors is a large bandgap semiconductor pixel detector. Sensor materials are CdTe or CdZnTe. These provide low-leakage current (and therefore low noise), are mechanically robust, and the high atomic number provides quantum efficiency near unity over the HXT bandpass.

The requirements of low threshold (to allow sufficient overlap with the SXT for cross calibration) and good spatial resolution dictate a pixel geometry with the sensor bump bonded to a low-noise custom ASIC readout. In this architecture, each pixel is connected to a separate readout channel on the ASIC chip by a small (25-micron) indium bump. The readout chip has identical dimensions as the sensor, with one channel occupying an area equivalent to the pixel size. The shield will consist of an inorganic scintillator (CsI or BGO) in a well configuration, read out by a photomultiplier tube operated in anticoincidence with the CdZnTe detector.

***TRL Status:*** The development of the Constellation-X pixel sensors is largely supported by SR&T under the HEFT balloon program. The HEFT program has invested seven years in developing a high-performance, custom low-noise ASIC and in CdZnTe pixel sensors with geometry essentially identical to that required for the HXT. Flight detectors have been fabricated and tested and will be deployed in Fall 2003. A large CdZnTe array will soon fly on the Swift mission. Although the detectors are of different architecture than planned for Constellation-X, the sensor material was flown on InFOCμS and EXITE and has been extensively tested for radiation tolerance (for monolithic rather than pixel sensors) and background properties.

The design of the low-noise custom ASICs is derived from the ACE CRIS/SIS instruments, and the logic and support processing system will fly on STEREO. Active scintillator shields have flown on numerous missions over the last 20 years, including GRO/OSSE, HEAO A-4, and Integral.

Based on the above discussion, the CdZnTe sensor material is at TRL 5, the pixel hybrid detector at TRL 4-5, and the shielding and other required systems at TRL 6.

#### 3.1.8.2 HXT Detector Technology Development Plan

***Strategy and Logic:*** Several areas require targeted development for HXT. The readout developed for HEFT has demonstrated that the low-noise required to achieve 1 keV spectral resolution at 6 keV is possible, the threshold on the current electronics is limited to ~10 keV by systematic noise. To operate as an imaging detector at 6 keV, individual pixel thresholds must be below 3 keV so that events with charge split between pixels can be reconstructed. Given the complexity of the readout architecture, this will take some iteration on the current design.

A second important area of development is in the sensor and contact fabrication. Large uniform CdZnTe crystals are difficult to obtain, and surface and bulk leakage currents vary by almost an order of magnitude sensor to sensor. Some of these problems may be solved with continued development of new growth techniques, new contacts, and new materials. It is therefore important to continue to evaluate new materials and contacts, such as CdTe with blocking contacts, and CdZnTe grown by high-pressure Bridgeman (HPB) techniques. This latter process produces very uniform material, albeit with high leakage current. The development of blocking contacts may allow both CdTe and HPB to be used for the HXT sensors.

Further work is required to evaluate the performance of both CdZnTe and CdTe in a radiation environment and to develop space-qualified packaging techniques. In particular, activation as well as changes in electrical properties resulting from increased charge trapping could be problematic. Mitigation may require incorporating a heating system to anneal the sensors periodically.

***Development Plan:*** The planned technology development steps are outlined below:

- **Detector Threshold–**Evaluate limits on current readout threshold; modify design and fabricate small prototype ASIC chip; fabricate full-sized chip.
- **Sensor Material–**Evaluate leakage currents and sensor performance for combinations of contacts and materials; evaluate charge trapping resulting from radiation exposure for different sensor/contact combinations.
- **System–**Fabricate flight-sized prototype; evaluate performance; test response to radiation environment, vibration tolerance, thermal response.

***Technology Investments to Date:*** Essentially the entire HXT detector technology development program has been funded through SR&T. This includes the development of a custom, low-noise readout, interconnect technologies, and CdZnTe sensor development, and evaluation of prototype detectors.

***Test Beds and Simulators:*** A prototype will be developed to serve as a test bed for the detector technologies. The fabrication steps will be carried out in facilities appropriate for flight production.

***Equipment and Facilities for Technology Development:*** The HXT detector program utilizes existing facilities at Caltech and GSFC. Caltech has developed an ASIC design and test facility, and laboratories for sensor packaging and hybridization. GSFC has an extensive facility for CdZnTe sensor material processing, contacting, and evaluation.

***Plans for Production Facility:*** No additional production facilities are required beyond those already in place for the technology development effort.

#### 3.1.8.3 Key Risks and Mitigations

The key technical risks during the HXT development phase are shown in Table 3-2.

**Low-energy threshold [HXT-1]** systematic noise currently limits threshold to ~10 keV. Mitigation is to redesign the electronics architecture (see Section 3.1.812).

### 3.2 Other Program Formulation Activities

The Constellation-X Project will successfully complete the formulation phase of the mission life cycle while complying with the NASA Procedure and Guideline (NPG) 7120.5B, NASA Program and Project Management Processes and Requirements, and the Goddard Directives for project management. The purpose of the formulation subprocess is to refine the preliminary mission concepts into an affordable program and plan that meet mission objectives and technology goals that are consistent with the NASA and Enterprise Strategic Plans. The Formulation Authorization Document (FAD), authorized by the Enterprise Associate Administrator, is the formal initiation of formulation.

The Constellation-X Project will perform the specific set of formulation activities in an iterative manner until mature products are delivered, appropriate information is baselined, and all requirements are met to successfully pass the established control gates, i.e., reviews. These major reviews serve as natural milestones for go/no-go decisions for proceeding onto the next step. As each step through formulation is completed, this process ultimately leads to the successful transfer into implementation.

Table 3-6 shows the list of Constellation-X formation products mapped to the major elements of the mission. The strategy for completing formulation is discussed in Section 4.1.1.6.

Table 3-7 lists the documentation to be prepared by the Project with references to the applicable reviews and governing management directives. Appendix B, page B-7 lists the major reviews that are held during formulation to assess levels of planning and readiness in order to proceed to the next formulation activity. A brief description of the major activities during formulation are described next. Project planning defines detailed program requirements and establishes program controls to manage the formulation subprocess. Systems analyses and life-cycle costing are conducted

**Table 3-6:** Constellation-X Formulation Products

| Management Concept | |
|---|---|
| • Responsibilities<br>• LOA (as required)<br>• International Management Agreement (as required)<br>• NASA/Partner/MOU (as required)<br>• Technology Investments<br>• Integrated Schedules<br>• Updated Staffing Plan<br>• Draft Science Management Plan<br>• Acquisition Strategy including make/buy of significant acquisitions | • Developmental Strategy<br>• Flight Assurance/Safety Approach<br>• Integrated Financial Management<br>• Configuration Control Approach<br>• Reserves Management Approach<br>• Independent External Reviews<br>• Outreach Strategy<br>• Updated Budgets including Life Cycle Cost<br>• Project Plan Outline |
| **Constellation-X Requirements** | |
| • Level 2 Requirements Draft<br>• Mission Success Criteria<br>• Minimal Mission<br>• Flight Segment Preliminary Performance Reqs | • Ground Segment Preliminary Performance Reqs<br>• Launch Segment Preliminary Performance Reqs<br>• Facility Requirements<br>• Verification Concept<br>• Calibration Plan |
| **Advanced Technology** | |
| • Technology Readiness Assessment | • Required Performance for each Advanced Technology |
| **System Engineering Management Concepts** | |
| • Software Development Strategy<br>• Draft Spacecraft Concept<br>• Draft Payload Concept<br>• Launch Vehicle Options<br>• Integrated Modeling<br>• Draft Verification Matrix | • Resource Allocation Process<br>• Draft Resource Allocations to Demonstrate Feasibility<br>• Interface Descriptions/ICD Outlines<br>• Technical Documentation Approach<br>• Draft Documentation Tree<br>• IV&V of Flight Software<br>• Traceability Methodology |
| **Mission Design and Operations Concept** | |
| • Data Reduction Plan<br>• Organizational Approach of Ground Segment<br>• Communications Strategy<br>• Orbital Parameters | • Data Collection Strategy<br>• Ground System Sizing<br>• Data Policy |

on concepts and options to meet program objectives. Technology assessment reviews the program concepts and technology requirements for feasibility, availability, security, technology readiness, opportunities for leveraging research and new technologies. Technology and commercialization planning identify technology, partnering, and commercialization options that satisfy the identified needs of the candidate concepts. Business partnership opportunities are identified in the development and operations elements of the program to satisfy program requirements. An assessment of the infrastructure, and a plan for upgrades/development are made to minimize program life cycle cost (LCC) by utilizing existing or modified infrastructure of NASA, other national and international agencies, industry, and academia where possible. Finally, the Project will perform knowledge capture which collects and evaluates process performance and also identifies process lessons learned.

**Table 3-7:** Formulation Documentation

| Document Title | Description | Referenced By | Due By | Update |
|---|---|---|---|---|
| Risk Management Plan | Provides a description of how risks will be identified, assessed, tracked, mitigated, and documented. | NPG 7120.5B | SRR | PDR/NAR |
| Software Management Plan | Describes the work to be performed and the resources needed to accomplish the goals and objectives established in the customer agreement. The Software Management Plan includes the design planning information and the process management information. | Flt Proj PM H/B dated 8/94, page A-2; NPD 2820.1, NASA Software Policies; GPG-8700.5, In-house Development and Maintenance of Software Products (pending release) | MDR | PDR |
| Configuration Management Procedure | Defines how Configuration identification Control Status Accounting and Auditing will be performed for a program or project. | NPG 7120.5B (paragraph 3.1.1.j) | SRR | PDR/NAR |
| Environmental Assessment | Document that ensures that environmental impacts have been considered in project planning and decision-making. | NASA Systems Engineering Handbook dated 6/1995, pp. 112-114; NASA Regulations (14 CFR Part 1216 Subpart 1216.3); NPG 8580.1, Implementing The National Environmental Policy Act and Executive Order 12114 | NAR | N/A |
| Mission Assurance Requirements | Present the safety and mission assurance (SMA) requirements that may be necessary for project. | 300-PG-7120.2.2A | PDR | CDR |
| Orbital Debris | Debris assessment addresses orbital debris generation that result from normal operations, malfunction conditions, and on-orbit collisions. Addresses provisions for post mission disposal. | NPD 8710.3, NASA Policy For Limiting Orbital Debris Generation; NSS 1740.14, Guidelines and Assessment Procedures for Limiting Orbital Debris | PDR | CDR |
| Program Commitment Agreement | Agreement between the Administrator and Enterprise Associate Administrator that documents the Agency's commitment to execute the program requirements within established constraints. | NPG 7120.5B, 2.1.1.2 | NAR | Annually validate |
| Program Plan | Approach and plans for formulating, approving, implementing, and evaluating the project. | NPG 7120.5B, 2.1.1.2 | PDR/ NAR | --- |
| Project Plan | Product of Project Formulation; describes implementation of a project. | NPD 7120.4B (para 1.e.1) NPG 7120.5B | NAR | --- |
| Safety Data Packages | Safety Data Packages are developed to demonstrate a payload's compliance with launch range requirements. For GSFC projects, Code 302, the Systems Safety and Reliability Office will either prepare or review the SDP's. | 302-PG-7120.2.1A, Systems Safety Support to GSFC Missions and Other Organizations | Mission Definition Review (MDRs) | CDR |
| Software Requirements Document | This document forms the basis for software design. | Flt Proj PM H/B dated 8/94, page A-2 | PDR | Contract Award and PDR |
| Software Test Plan | This document lists the procedures used to test and validate software. | Flt Proj PM H/B dated 8/94, page A-3 | PDR | CDR |
| System Engineering Management Plan | This document contains trade studies, technology studies, system verification and test plans, and interface requirements. | SEU Program Office Requirement | PDR | CDR |
| Technology and Commercialization Plan | This plan describes the establishment of partnerships to transfer technologies, discoveries, and processes with potential for commercialization. | NPG 7120.5B (para 2.1.4) | PDR/ NAR | NA |